HAMILTON HARBOUR STUDY '75

FIRST YEAR MIXING

SECTION B:
Artificial Mixing

Ministry
of the
Environment

Ontario

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HAMILTON HARBOUR

Artificial Mixing Report

If it cannot be expressed in figures;
it is not science, it is opinion.

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SECTION B
ARTIFICIAL MIXING OF HAMILTON HARBOUR 1975

SUMMARY

HAMILTON HARBOUR ($79^{0}50'$W, $43^{0}17'$N) IS AN ENCLOSED BODY OF
WATER CONNECTED TO THE WESTERN END OF LAKE ONTARIO VIA A
SHIPS' CHANNEL. LAKE EXCHANGES OF THE ORDER OF 1 PERCENT OF
THE HARBOUR VOLUME PER DAY, AND AVERAGE INTERNAL CURRENTS OF
3 CM SEC^{-1} PREVENT STABLE TEMPERATURE LAYERS OF WARM SURFACE
WATERS AND COLD BOTTOM WATERS FROM FORMING. IF SUCH LAYERING
IS ESTABLISHED, THE BOTTOM WATERS BECOME DEPLETED IN DIS-
SOLVED OXYGEN. BECAUSE OF THE NATURAL INSTABILITY OF THESE
STRATA, HOWEVER, EFFECTIVE ARTIFICIAL MIXING REQUIRES LITTLE
ENERGY TO CIRCULATE THE HARBOUR WATERS. DURING 1975,
ARTIFICIAL MIXING WAS SUFFICIENT TO WEAKEN THE STRATA TO THE
EXTENT THAT DISSOLVED OXYGEN WAS RETURNED TO THE LOWER
DEPTHS OF THE HARBOUR. THIS REAERATION WAS ACCOMPLISHED
WITH AN AIR DIFFUSER BY LIFTING THE DENSE LOWER WATERS TO
THE SURFACE WHERE ATMOSPHERIC AERATION INCREASED THE DISSOLVED
OXYGEN CONTENT.

AN INTENSIVE SURVEY OF PRIMARY NUTRIENTS, HEAVY METALS,
MINERAL CONTENT, PHYTOPLANKTON ABUNDANCE AND PRODUCTION, AND
BACTERIAL POPULATIONS WAS PERFORMED. RELATIVE ABUNDANCE OF
ZOOPLANKTON AND FISH POPULATIONS WAS DETERMINED. DURING THE
LIMITED PERIOD OF MIXING (JULY-AUGUST, 1975) DISSOLVED
OXYGEN INCREASED FROM NEAR 0 MGL^{-1} TO 2 MGL^{-1} THROUGHOUT THE
LOWER WATER COLUMN. THERE WERE NO SIGNIFICANT CHANGES IN
HEAVY METALS AND MINERAL CONTENTS, BUT TOTAL PHOSPHORUS
CONCENTRATIONS BECAME MORE HOMOGENOUSLY DISTRIBUTED WITH
DEPTH, DECREASING SURFACE CONCENTRATIONS. PHYTOPLANKTON
PRODUCTION AND STANDING CROP INCREASED, AND BACTERIAL
POPULATIONS DECLINED. ZOOPLANKTON INCREASED THEIR VERTICAL
HABITAT BUT FISH, HOWEVER, BECAUSE OF THE LIMITED PERIOD OF
MIXING DID NOT RESPOND. IT WAS APPARENT THAT ARTIFICIAL
MIXING INCREASED THE WASTE ASSIMILATION POTENTIAL OF THE
HARBOUR.

HAMILTON HARBOUR ARTIFICIAL MIXING REPORT

Recent studies by the Ontario Ministry of the Environment
have indicated that hypolimnetic anoxia is a critical factor
influencing the water quality of Hamilton Harbour. In the
first Hamilton Harbour Report (MOE 1974) artifical mixing
was suggested as a possible method to assuage hypolimnetic
anoxia. A review of artifical mixing presented in the second
study report (MOE 1975) indicated that responses to arti-
ficial mixing were varied. A survey by the American Water
Works Association (1970) indicated the 90% of mixing trials
were considered successful with respect to improved water
quality and biological production. Because of the complexity
of the physical-chemical-biological interactions in Hamilton
Harbour and varied responses to artifical mixing, it was
not possible to predict the effects of vertical circulation
of the harbour waters.

Hamilton Harbour is an unique body of water. It is a natural
harbour, sheltered from Lake Ontario by a narrow sandbar.
The harbour has a volume of 2.8×10^8 m^3 and mean depth of
13 m. Industrial water use is estimated to be 27 m^3 sec^{-1},
with waste waters returned into the harbour. Treated urban
wastes enter the harbour directly at a rate of 3.2 m^3 sec^{-1}
with an additional annual loading of 0.1 m^3 sec^{-1} from storm
sewers during overflow periods. Nitrogen loading was
determined to be five times the harbour stock, and phosphorus
loading was thirty times higher than the calculated
harbour stock. Much of the nutrient loading was into the
epilimnion of the harbour, and artifical mixing was suggested
as a means to reduce epilimnetic concentrations and increase
the capacity of the harbour to assimilate these high effluent
loadings by providing a suitable environment for aerobic
decomposition.

The primary effects of artifical mixing are basically dependent
on the total energy used for mixing and the efficiency of
the transfer of this energy to the water mass. As stratification
is a cumulative process, the energy input required for
destratification must be greater than the rate at which the
energy of thermal stabilization is increasing. If the input
of the mixing system and natural turbulence is equal to or
is less than the energy of stratification, the rate of
increasing thermal stabilization will be zero or correspondingly
reduced. In this respect the terms artificial mixing and
destratification are not synonymous. Most mixing attempts
are designed to destratify the water column, although
systems have been designed which can prevent stratification
or maintain a certain degree of thermal stabilization.

It is possible that chemical reactions, as described by Stumm and Morgan (1970), can be predicted within a body of water. Most of these reactions are either adsorption and precipitation, complexation, oxidation and reduction, acid-base reactions, and biotic absorption and assimilation. It is the last component which places the artificial mixing of Hamilton Harbour or any body of water into the realm of being experimental design. Chemical and physical responses could be predicted from basic thermodynamic relationships, if these parameters were not interrelated with the biota of the harbour.

During periods of stratification, Hamilton Harbour is characterized by a number of horizontal isodensity strata. Perturbations between the strata are primarily induced by wind mixing and exchange via the ship channel (MOE,1975). The theoretical effects of diffused air injection were described by Fast (1968). Basically, cold hypolimnetic waters are brought to the surface as a result of decreased density and entrainment with the bubbles from the diffuser. At the surface the upflow of water diverges and begins to sink below the warm epilimnetic waters. This downwelling is modified by the density strata, and at all times mixing occurs between the upwelled water and epilimnetic waters, forming new density strata. Koberg and Ford (1965) have noted that the rate of destratification decreases as a lake approaches isothermal conditions.

The review of artificial mixing in the Hamilton Harbour Report 1975 noted that unsuccessful attempts to relieve hypolimnetic anoxia are often the result of a poorly estab-lished oxidized microzone at the sediment-water interface. This would suggest that the sediment oxygen demand (both chemical and biological) might well be the driving force of oxygen depletion in the harbour, and oxygen demand within the water column to be a secondary factor. In Section E of the report it was found that oxygen uptake rates of 0.05 grams of oxygen m^{-2} hr^{-1} were sufficient to deplete the total oxygen stocks of the harbour, were it not for photo-synthetic sources and mass exchange by the ship canal. It must be noted that photosynthesis is probably of little value to the oxygen budget as net oxygen production (photo-synthesis minus respiration) could be low in the optically deep waters. Owens (1969) estimated that 69 percent of the oxygen content in the Thames estuary was derived from atmospheric reaeration, and only 8 percent from phytosynthetic sources.

Within the water column artificial mixing can result in rapid oxidation and utilization of dissolved organic carbon. There are few studies on the effects of artificial mixing on the nature of the sediments. Fast et al (1972) found that

sediments were gelatinous and adhesive before aeration, and became loose after aeration as a result of a change from anaerobic to aerobic decomposers. Mercier (1955) was reported by Toetz et al (1972), to have stated that sediment thickness of Lake Brett was decreased as a result of maintaining an aerobic microzone over a period of years. This would suggest that organic sediment oxygen demands can be alleviated by artificial mixing, and in this aspect mixing can be considered as a corrective process. Hamilton Harbour receives the effluents of three sewage treatment plants (the Dundas plant via Cootes Paradise, the Burlington Skyway plant and the Hamilton plant). It is probable that much of the organic nature of the sediments predates the Hamilton STP when raw sewage was discharged directly into the harbour. The sediments are high in organics as noted by loss on ignition data as high as 18 percent of the sediment content.

In general terms, artificial mixing, be it in a form a destratification or induced vertical mixing, increases the assimilation capacity of a body of water by creating 'sinks' (such as the loss of carbon dioxide, hydrogen sulphide, and ammonia to the atmosphere, and the loss of metals such as iron, manganese and aluminium to the sediments). It is not known just how efficent these processes are as many of these losses can be balanced by changes in chemical turnover rates, biotic adaptations and modifications of the thermodynamic equalibria of physical-chemical parameters.

Biological responses can dictate the success of artificial mixing when considering water quality whether it be for recreational purposes (Hooper et al, 1953) or for water supply (Ridley 1970, Steel 1972). Vertical circulation of a water column can change temperature regimes, light penetration and nutrient availability in a body of water. Empirical predictive models of phytoplankton responses have been developed, (Lorenzen and Mitchell, 1975), but these do not account for the large variations and responses outlined in the literature.

The effects of artificial mixing are not only palliative, and the success of artificial mixing must be based on an overview of the problem. Hamilton Harbour represents a very difficult ecological situation. The heavy input of nutrient organics and thermal effluents combined with land filling operations have all contributed to the low water quality. In Hamilton Harbour artificial mixing is a treatment of the symptoms of eutrophication. To be considered successful, the mixing project must prevent hypolimnetic anoxia. Although not a corrective process, increased assimilation capacity and improved biological activity resultant from artificial mixing might reduce the deleterious effects of nutrient and waste loadings on water quality.

THE MIXING SYSTEM

Four diffuser lines were used to induce artificial mixing in Hamilton Harbour. The aerator lines were placed 61 m (200 ft) apart extending from the west wall of Stelco docks. Each line consisted of 5.08 cm (2 in) polyethylene tubing (80 psi working pressure). Three of the lines consisted of a 191 m (625 ft) delivery section attached to a 305 m (1000 ft) perforated line. The fourth line consisted of a similar delivery line with a 122 m (400 ft) perforated line. A 137 m (450 ft) steel header pipe connected the lines to a 0.28 m^3 sec^{-1} (600 cfm) compressor which was used to supply the aerator lines (Fig. 1).

Perforations were made in the diffuser section using a punch tool of 2 mm length and 0.35 mm width. Each 305 m (1000 ft) of aerator line contained 1465 slits. Starting from the far end of the diffuser, the slits were arranged as below:

1st   400 slits at 10.2 cm (4 in) intervals
2nd   600 slits at 20.3 cm (8 in) intervals
3rd   465 slits at 30.3 cm (12 in) intervals

This spacing was computed to obtain an even distribution of air flowing through each metre of diffuser at the operating air pressures. The diffuser line was kept approximately half a metre off the bottom, and was anchored at 4.5 m (15 ft) intervals by attached cement blocks.

Water pressure at a depth of 24.4 m (80 ft) of water is approximately 2.31 atmospheres (34 psi), and combined with losses to the line of approximately 1.02 atmos (15 psi), there is an internal design pressure of approximately 3.4 atmos (50 psi). As the compressors should be operated at under 5.4 atmospheres to prevent oil in the line, the pressure available at each aperature is 0 to 2.0 atmos (0 to 30 psi). Extensive tests at the Ontario Hydro Hydraulics Laboratories suggested that the mean flow at each aperture would be between 23-39 cm^3 sec^{-1} (35 cfh) at 0.8 atmospheres (12 psi) assuming 0.047 cm/sec^{-1} (100 cfm) at atmospheric pressure from the compressor to each line.

Figure 2 is a schematic representation of the dates of installation of the four aerator lines. The lines were numbered consecutively from the north most position. The operation of the diffusers was affected by shipping in the docking area which severed the lines on several occasions. Only towards the end of July 1975 were all lines operating effectively with a 0.17 m^3 sec^{-1} (350 cfm) total flow. At this rate of flow assuming an entrainment factor of 10, it would take approximately 700 days to mix the epilimnetic and hypolimnetic volumes of the harbour at this time of year.

On its own the mixing system is inadequate but other physical factors; such as higher entrainment factors, advective flow, exchange periodicities at the thermocline and wind stress modify the physical behavior of the water mass, producing less stable water masses then would be expected. In shallow parts of the harbour (less then 10 meters) these factors alone could produce several complete destratifications each year. These destratifications are periodic and are related to the geometry of the harbour and periodicities of Lake Ontario. In many circumstances the extra work required to maintain isothermal conditions is only 3-4% of the surface wind work (Steel, 1972); provided some mechanism exists for transforming shear through the thermocline. The alteration of the isodensity strata would be such a mechanism to induce greater wind work which generates currents and increases the advective processes in the water body.

THE RESULTS OF ARTIFICIAL MIXING

a.   Temperature and Dissolved Oxygen

The primary effect of artificial mixing is the modification of the density strata within the body of water. The usual sequence of events would be the lowering of the thermocline. The time required to lower the thermocline until achieving isothermy, depends on factors such as volume, stability of stratification, intensity of solar radiation, wind effects etc. Generally, there is a surface cooling effect and an increase in the temperature of the hypolimnetic waters. Surface cooling was evident in Hamilton Harbour, as the surface temperatures dropped from 26°C to 22°C (Fig. 3). Although there was an atmospheric disturbance on July 25, (Fig. 2) it is doubtful if this drop in mean air temperature could result in such cooling effects. An intrusion of warm eplimnetic water into the hypolimnion was noted in July, but this was probably related to natural mixing. The lack of any good indication of an increase in hypolimnetic temper- atures (increased 4°C) was a result of the shallow depth of the epilimnion ($\sim$ 6 m) as compared to the hypolimnion ($\sim$ 14 m). It is apparent that the shallow stations 270 and 252, of 12 meters and 6 meters depth respectively, do not form stabilized water columns. Only the deep basins (as demonstrated at stations 258 and 4) have density strata which are somewhat stabilized. Station 4 has the highest temperatures within the water column as it receives the warm effluent of the Windermere Basin.

The artifical mixing of Hamilton Harbour, during the period of July to August 16, did not result in any major changes in the thermal structure. As the water column of the harbour is naturally unstable (MOE, 1975), it was difficult to determine which changes were related to the mixing experiment.

In Figure 2 (mean wind and air temperatures), it is noted there is no evidence of atmospheric changes such as high winds or substantially low temperatures to account for modifications in the thermal profile. Thus, artificial mixing probably accounted for the modest alteration of the iso-density strata.

One of primary objects of artificial mixing is aeration. The efficiency of aeration depends on the oxygen tensions existing in the water (Roeber et al, 1965). It is not known if the diffuser was a significant source of oxygen, but without doubt surface exchange dominated the aeration aspect of artificial mixing of Hamilton Harbour. The pumping rate was small compared to the harbour volume. Even if 20% of the oxygen was absorbed by the water, less than 0.1 mgl^{-1} of oxygen would be added to the harbour after one week of aerating at a rate of 0.17 m^{3}sec^{-1} (350 cfm).

The dissolved oxygen content of Hamilton Harbour increased during vertical circulation of the harbour waters. On July 18 with two diffuser lines operating there is a well defined anoxic hypolimnion (Fig. 4). There is a slight increase in dissolved oxygen content at the bottom of Station 4 perhaps as a result of influences of Lake Ontario water. On July 21 there was a marginal improvement of station 4, as the hypolimnetic oxygen concentration increased to 1.0 mgl^{-1}. On July 31, however, with four diffuser lines operating all stations had measurable dissolved oxygen concentrations (greater than 1 mgl^{-1} throughout the water column). During the first week of August only two diffuser lines were operating (lines 1 and 4) and anoxic conditions returned. Frequent damage by ships to the aerator left only one line functional by August 16. On August 19, the one remaining line failed. After being repaired and repositioned, line 1 operated from August 22 to the end of September with little effect on the dissolved oxygen content. From these observations, it was demonstrated that a flow of air in excess of 0.14 m^3 sec^{-1} (300 cfm) was required to have a beneficial effect on the hypolimnetic anoxia. Because of the short period of operation of the four lines, there was little measurable improvement in the overall standing stock of dissolved oxygen. Considering the warm summer compared to previous years, the beneficial effects of artificial mixing would probably be disguised by increased oxygen demand. It must be noted that artificial mixing was successful in increasing the dissolved oxygen content of the harbour in a very short period of time. Continuous vertical circulation could be expected to restore the dissolved oxygen to the extent that the fish and zooplankton habitats would be extended to greater depths.

Changes in the dissolved oxygen content of Hamilton Harbour have been related to lake water incursion through the ship canal. To resolve whether the increase in the dissolved oxygen content of the harbour was related to lake water incursions or artificial mixing, redox potential was used to differentiate the two water masses. Figure 5 illustrates the redox potential at three stations during the mixing period. Redox potentials are difficult to interpret, but in general, can be expected to be in the range of 400-500 mv for oligotrophic lakes such as Lake Ontario with the actual value being dependent on the oxygen-hydroxyl system as outlined below:

$$O_2 + 2H_2O + 4e = 40H$$
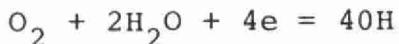
$$Eh = 1.234 - (0.058\ pH) - (0.0145\ log\ Po)$$

where Po is the partial pressure of oxygen.

In Hamilton Harbour, the Eh values measured are about 200 mv and clinograde Eh curves occur suggesting little influence of Lake Ontario at the sampling stations. Hutchinson (1957) indicated that low Eh, with clinograde distributions, was dependent on other redox systems. The redox potentials of Hamilton Harbour might well be dependent on the Fe^{++} - Fe^{+++} and nitrate-ammonia systems with the presence of sulphide and/or dissolved organic material resulting in further complications. It is possible that the Eh of the waters would have to be raised to a critical level before the dissolved oxygen concentration would increase. Artificial mixing resulted in orthograde Eh profiles (See Fig.5). Under conditions of orthograde Eh, the absolute value of Eh is important at the sediment-water interface as it influences the solubility of nutrients in the sediment. It is by this parameter that the establishment of an oxidized microzone at the interface can be determined.

B.   Responses of Nutrients and Heavy Metals

The distribution of non-conservative parameters often reveal varying degrees of over-dispersion (variance > mean). Departure from Poisson distributions can either be positive or negative. As a result of sedimentation, current and turbulence patterns resulting in non-equal mixing, effluent outfalls and shoreline effects; over-dispersion is frequently encountered in aquatic habitats. When trying to statistically assess significant relationships between any parameter and artificial mixing, it is extremely difficult to determine if a change in concentration or distribution of a certain parameter is related to artificial mixing. In the following discussion there has been no attempt to statistically relate the chemical or physical changes to artificial mixing. Chemistry and statistical trends will be more fully discussed in a separate report.

All metals were monitored as depth composites at stations 252, 4, 270 and 258 at regular time intervals during 1975. Lead and molybdenum, cadmium, copper, chromium, manganese, cobalt and nickel concentrations did not illustrate any definite response to artificial mixing. Zinc increased during the mixing period, but this might be a result of increased atmospheric loading into Hamilton Harbour, however, no data were available in 1975. Shiomi and Kuntz (1973) found that atmospheric loading was a significant source of zinc in Lake Ontario. Chloride, sulphate, magnesium, calcium, potassium and sodium were not monitored intensively enough to note any effects of artificial mixing. It was noted by Haynes (1973) that calcium, magnesium, potassium and chloride were not affected during the artificial mixing of Kezar Lake. It must be noted, however, that calcium can have varied responses (Fast 1971, Symons, Irwin and Robeck 1968).

The distribution of iron is outlined in Figure 6. It is often reported in the literature that iron and manganese concentrations decreased during periods of mixing (Symons, Carswell and Robeck, 1969; Wirth and Dunst 1967). The decreases are usually related to the moderately soluble Fe^{++} being oxidized to the relatively insoluble Fe^{+++}. In Hamilton Harbour there was no evidence of a decline in total iron concentrations. Similar results were found by Lackey (1972) who noted that levels of iron and manganese did not change substantially in an artificially mixed lake. As a result of high iron loadings into the harbour and the relatively short period of mixing, it is reasonable to assume that changes in iron concentrations would not be expected.

In some circumstances, induced vertical mixing can result in definite responses by nutrients associated with phytoplankton production (Haynes, 1973). Although the components of the mineral contents of the water are necessary for phytoplankton production, the biogeochemical cycling of these elements is not directly related to these organisms, and concentrations are seldom, if ever, limiting. The different responses of calcium, however, might be a result of precipitation when autotrophs assimilate CO_2 from the system.

Elements related to biological processess often assume unpredictable distribution as a result of artificial destratification. This is particularly true of phosphorus. As phosphorus has high turnover rates, it is difficult to determine nutrient limitations by measuring the standing quantity of phosphorus. Changes in concentration are not simply related to algal production, as precipitation, adsorption and redox reactions occur. It is necessary to have mass balance budgets before a response to artificial mixing can be quantified. Most reports on the effects of artificial

mixing on phosphorus relate to changes of distribution
(Hooper et al 1953, Leach and Harlin 1970) and not to
changes in concentration (Bernhardt and Hotter 1967; Haynes
1971).

There were no distinct trends in the total phosphorus or
soluble phosphorus during the period of induced vertical
mixing in Hamilton Harbour. In Figure 7a soluble phosphorus
appears to have a high degree of temporal and spatial
contagion. It is difficult to relate this distribution to
biological activity, but it was noted that the periods of
minimum soluble phosphorus were associated with high bacterial
activity on June 4 and high phytoplankton standing crops on
July 16. In general, however, there appears to be no strict
relationship between changes in phosphorus concentration and
biological production. It is expected that phosphorus
loadings are so high that changes in concentration and
distribution are more related to precipitation or changes in
loading rates.

Figure 7b illustrates the vertical profiles of total and
soluble reactive phosphorus at Station 258. Before diffused
air was injected at a rate of 0.14 m^3 sec^{-1} (300 cfm)
epilimnetic concentrations of total phosphorus exceeded
hypolimnetic concentrations. On July 31 epilimnetic concen-
trations were comparable to hypolimnetic concentrations. As
the vertical profile of chlorophyll a (Figure 15b) does not
correspond, it would appear as if the modification of the
total phosphorus profile is not simply related to the
redistribution of the phytoplankton.

Dissolved silica levels are often stratified in natural
lakes as a result of the wax and wane of diatom populations.
This is well represented in Figure 8 which reveals decreasing
concentrations of silica during the spring diatom growth,
resulting in low concentrations in the epilimnion and high
concentration in the hypolimnion.

As silicates do not depend on a reduced environment to
become soluble (Cheng and Tyler, 1973), there were no
definite response to artificial mixing. During the period
of July 16 to July 23 silicates were evenly distributed with
depth. This might well be related to artificial mixing, but
it is quite likely that other physical parameters were
operating.

The nitrogen cycle of Hamilton Harbour is strongly dependent
on biological activity. Changes in the ratio of NO_3:NO_2:NH_3
reflect the composition and activity of the bacterial flora
of the harbour as well as industrial loading. This is
particularly true during the winter period as ammonia
concentrations increase as a result of industrial loadings
and the low activity of the nitrifiers. From the spring to

the autumn there is a decrease in ammonia perhaps as a
result of increased activity of nitrifiers and some direct
uptake of ammonia by the phytoplankton.

Nitrate values were slightly higher in 1975 than in 1972.
Before hypolimnetic anoxia was developed (June 4), nitrate
concentrations were greater in the hypolimnion than in the
epilimnion, probably as a result of phytoplankton assimilation
in the upper density strata. Once anoxia was developed,
however, nitrates were reduced as denitrification rates
increased. Figure 10 illustrates that during the mixing
period there was no associated response by nitrates.
Sustained artificial mixing might well have favoured nitrifi-
cation processes, representing a positive response of the
harbour to artificial mixing. The nitrogen system is
suspected as being an important contributor to the low Eh.
A shift towards nitrate would represent a positive response
of the harbour to artificial mixing.

Nitrite is a relatively unstable intermediate in the nitrate-
ammonia system. Although it is usually recorded in low
concentrations, nitrite accumulates in Hamilton Harbour and
reaches concentrations of 1.85 mgl^{-1}. This chemical environ-
ment is reflected by the low Eh measurements. The activity
of faculatative anaerobic bacteria can have a profound
effect on the behaviour of the nitrogen species. Paine and
Riley (1969) felt that nitrates suppressed the reduction of
$NO \rightarrow N_2O$ in Pseudomonas, and a similar phenomenon in Hamilton
Harbour might explain the accumulation of nitrite.

As organic compounds are the energy source for heterotrophic
organisms and inorganic compounds such as nitrates serve as
electron acceptors, this aspect of the nitrogen cycle
interacts to alter the dissolved organic levels in the
water. Combined with artificial mixing these processes can
improve water colour problems.

C. Turbidity

Hamilton Harbour has moderate levels of turbidity of 1-6 FTU
as illustrated in Figure 12. These values are low considering
the high vertical attenuation coefficients (ln units m^{-1})
recorded during 1975 of (0.52-1.58). Although turbidity is
to some extent dependent on phytoplankton concentrations,
there is a poor relationship between chlorophyll a and
turbidity. There is an increase in turbidity during the
mixing period, probably as a result of suspended sediment.
This observation was confirmed by microscopic analyses which
indicated an increased number of empty diatom frustules
which had been lifted off the sediment. Despite the increased
turbidity, there was actually a decline in the vertical
attenuation coefficient suggesting that water color problems
were reduced by the mixing processes.

BIOLOGICAL RESPONSES

Unknown environmental synergisms affecting biological
production constrain predictions. Predictive models of
biological responses have assumed that changes in light or
nutrient availability are the dominating factors. In such
models, there is no consideration of the stress of a chang-
ing environment or adaption of organisms to mixing.

For many species, artificial mixing results in increased
habitat volumes for exploitation. Some organisms, however,
such as cold water fishes have their habitats destroyed and
are selected against by such procedures. In optically deep
waters, complete vertical circulation can basically negate
phytoplankton production, yet in optically shallow waters
circulation enhances phytoplankton production. These are
the principal considerations to be resolved before artificial
mixing is undertaken.

Perhaps the most important aspect of artificial mixing are
the induced changes in the bacterial populations. The
composition distribution and abundance of bacterial popu-
lations in Hamilton Harbour have strong effects on the
harbour's water quality. Despite this importance, the
response of bacteria to artificial mixing has generally been
poorly documented. Nutrient cycles, biological oxygen
demand and total biological production are dependent on the
bacterial content of Hamilton Harbour. Because of this
dependency, it is essential to determine what changes in the
structure of the bacterial communities result from artificial
mixing.

During 1975, total coliform, fecal coliform, fecal strepto-
cocci, Pseudomonas, heterotrophs, Nitrosomonas, sulphate
reducers and sulphur oxidizers were determined. Populations
were monitored at four stations, samples being collected at
the surface and at one meter from the bottom of the water
column. As station 258 was located near the diffuser and
was representative of the central basin of the harbour, it
was selected to be indicative of the effects of artificial
mixing.

Figure 13 a and b illustrate comparative and absolute
changes within the communities. It is noted that total and
fecal coliform counts are higher for the epilimnetic than
the hypolimnetic waters (Figures 13 c and d). This is to be
expected since the warm sewage effluent will tend to flow
over the cooler hypolimnetic waters. As the hypolimnetic
waters contain populations which are often within the limits
for total body contact recreation one expected result of a
good period of artificial mixing would be to "dilute"
surface concentrations. On July 31, during the period of
most intensive mixing, there was a decrease in surface and

bottom bacteria counts. It is not known if the decrease in concentrations was a direct response to artificial mixing (i.e. dilution) or was an indirect response (initial change in the chemical environment with a secondary response by the bacteria). The latter explanation was accepted as even the hypolimnetic populations decreased, an observation not accounted for by the dilution theory.

There was a decline during the mixing period in the population size of the various monitored taxons excluding the sulphur oxidizers. This response was not confined to station 258, as stations 4 and 252 revealed declining populations at the same time with only sulphur oxidizers being abundant. Station 270 did not indicate a similar trend.

Thiobacillus thioparus (sulphur oxidizer) became less abundant during the onset destratification and the development of anoxic conditions. During July, at Station 258, there were increases in numbers during the entire period of artificial mixing. It is expected that some aspect of this physical-chemical environment have been modified to increase the growth potentials of T. thioparus. Whether the changes in Eh as outlined in Figure 5 were associated with this modification is not known, but it would appear that minimal mixing can produce desired changes within the bacterial population.

Most studies on eutrophication emphasize the response of phytoplankton to increased nutrient loads. Artificial mixing has been reported to increase phytoplankton standing crop (Hooper et el, 1953; Johnson, 1966; Fast et al, 1972) in some instances, and reduce the size of standing crops in others (Lackey, 1971; Ridley, 1972). These apparently conflicting findings ensue from the variety of applications of mixing.

Algal productivity during mixing has been studied by Fast (1971) and Haynes (1975). Although it has been generally agreed that primary productivity increases during mixing periods because of improved nutrient availability and light penetration, there are times where decreased productivity occurs especially when associated with deep vertically circulated water columns. Mixing depth is a critical factor when managing algal production. Talling (1971) and Murphy (1962) noted reduction in standing crop occur when the mixing depth is greater than the compensation depth at which the rate of photosynthesis equals the rate of respiration. Toetz (1972) speculates that artificial mixing accelerates both the rate of energy flow and nutrient cycling.

Productivity measurements in Hamilton Harbour were performed by Dr. G. Harris of McMaster University. Table 1 presents strong evidence to suggest that high phytoplankton productivity was associated with the onset and end of the mixing period.

Table 1: Calculated Assimilation Numbers Determined in Hamilton Harbour, 1975 (mg. CO_2, mg chlor. $\underline{a}^{-1}$, hr^{-1})

Date	Assimilation Number
July 7, 1975	5.5
July 14	30.6
July 21	26.7
July 28	15.9
Aug 11	9.1
Aug 18	30.5
Aug 25	8.3

Productivity at station 270 was initially very high on July 14 with only one diffuser line operating. During July, there was a decline in the assimilation numbers perhaps reflecting nutrient utilization (nitrate depletion was observed on one occasion during July), or increased depth of vertical mixing as there was a definite tendency for Station 270 to tend toward the continuous temperature gradient during this period of mixing.

Phytoplankton standing crop was determined by direct microscopic counts using the Utermohl technique with split sedimentation chambers. Chlorophyll $\underline{a}$ measurements were made to support the microscope data as chlorophyll $\underline{a}$ was not in itself a reliable measure of standing crop.

During the last week of July with all the diffusers operating there was a distinct change in the phytoplankton composition and abundance. In late June to early July Lagerheimia longiseta (Lenn.) Printz. was replaced by Oocystis borgei Snow. and Rhodomonas minuta var. nannoplanctica Skuja. These species dominated the phytoplankton until late July when a large, relatively isolated growth of Ankistrodesmus falcatus (Corda) Ralfs. and possibly Ankistrodesmus braunii (Naeg.) Brunn. occurred. A third species became common during this period and was tentatively identified as Kirchneriella spp. (see Fig. 14).

Calculated algal volumes on July 28 were 8.0×10^7 cm^3 ml^{-1}, a peak for the entire survey. It should be noted, however, that the chlorophyll $\underline{a}$ data do not illustrate this (see Figure 15a). This indicates that chlorophyll is not a consistent estimate of standing crop unless supported by other techniques.

Artificial mixing altered the periodicity, abundance and composition of phytoplankton standing crops. Although it is unlikely that phytoplankton were responding to changes in the mixing regime, they might well have been responding to secondary effects such as nutrient availability. The pulse of Ankistrodesmus was of short duration and erratic distribution as it was not abundant at Station 252 or 270. This type of response suggests that the effects of artificial mixing were more noticeable in the deep water stations, and might have had little effect in the shallow stations which can be destratified at any time during the summer should wind mixing be sufficient.

Determining the effects of artificial mixing on zooplankton populations would involve determining the modifications resulting from changes in temperature, dissolved gases, light, predation and competition. Fast (1971) concluded that destratification extended the vertical distribution of zooplankton. This is similar to the situation in Hamilton Harbour, as a peak zooplankton biomass (0.0389 m^{-1}) occurred during July 21-July 28. It would be dangerous to attach too much significance to this peak, as the temporal and spatial distribution of zooplankton exhibited marked fluctuations (Fig. 16). Volume samples collected by McMaster University indicated that zooplankton populations were vertically extended.

In some circumstances, aeration has resulted in species indicative of more oligotrophic conditions becoming common (Linder and Mercier, 1954), but this did not occur in the harbour. There can be little doubt that the mixing project did, in fact, increase the habitat boundaries of the zooplankton. The composition of the populations is basically dominated by rotifers, with cladocerans and copepods being relatively scarce. McNaught et al (1975) has observed that many cladocerans such as Daphnia and Bosmina tend to be rare in urban and industrial areas.

Zooplankton and fish populations are expected to have a much slower response to artificial mixing. Artificial mixing is becoming very common in the fisheries aspect of lake management (Hooper et al, 1953; Grim, 1952; Fast, 1966, 1971; Irwin et al, 1967; and Lackey, 1971). The habitat of fish is basically determined by food availability, but as stratification occurs, the lake strata of desirable temperature and dissolved oxygen content are decreased and this contracts the viable habitat volume. Summer die-off is related to anoxia, limited algal production, algal toxins, and fungal diseases; situations which are altered by artificial mixing. As noted in the section on temperature and dissolved oxygen, there was not sufficient change in these parameters to result in increased fish habitat.

With regard to Hamilton Harbour, a fish netting by the Ministry of Natural Resources found a relatively low abundance of fish. Nettings in July were completely unsuccessful indicating that the vertical habitat of fish was not extended. Until dissolved oxygen content increases to 3-5 mg/l for a long period of time, and toxic dissolved gases such as ammonia and hydrogen sulphide become less abundant, there can be little or no change in the fish population. It is of value to note that in a body of water as anoxic as Hamilton Harbour, destratification would probably deplete the fish population. A rapid intrusion of anoxic hypolimnetic water would result in the suffocation of the resident fish population. It is because of this, artificial mixing must be on a slow basis and destratification not be a desired situation. By preventing stratification or by lowering the rate at which column stabilization is increasing, artificial mixing can prevent such stress situations.

SUMMARY AND FUTURE CONSIDERATIONS

The period of artificial mixing of Hamilton Harbour was too short to have ameliorated any water quality problems for any appreciable length of time. The 1975 mixing experiment was not seeking destratification as an end goal, but rather to relieve the condition and symptoms of hypolimnetic anoxia. Secondary effects of this aeration aspect would indicate that the aeration can actually increase the assimilation potential of the harbour. This study confirms Toetz's (1972) hypothesis that mixing enhances energy flows within the system, and if the data to date concerning the relation of artificial mixing to improved water quality are an accurate guide, mixing will be beneficial for immediate problems and perhaps corrective in the long term.

Artificial mixing will be continued in Hamilton Harbour in 1976. Repositioning of the aerator lines to extend from the north wall of Stelco will minimize damage from ships. The actual diffuser sections would be in the same deep basin, and the lines would cross the shipping lanes in deep water.

The responses of Hamilton Harbour to artificial mixing were:

1. Mixing of hypolimnetic and eplimnetic waters without destratification.

2. Increased dissolved oxygen concentrations, but as a result of the short period of mixing there was little change in the dissolved oxygen budget.

3. Although no direct changes were determined with heavy metals, this can be considered as a positive response, as one of the problems of artificial mixing is a resuspension of heavy metals adhered to fine particles. There appears to be some increase in turbidity but this

is quite likely related to algal biomass and small amounts of resuspended sediments. There were no indications of precipitation of oxides of the heavy metals monitored.

4. There was little change in alkalinity, pH or conductivity. The only component of conductivity which is theoretically expected to change is calcium, but this was not observed in practice.

5. Changes in nutrient concentrations and distributions were suspected because of changes in algal productivity. Vertical distributions of total phosphorus were altered. Hypolimnetic filtered reactive phosphorus increased suggesting that sediment release was still occuring during the mixing period.

6. Bacterial populations generally declined during the period of intensive mixing, but showed no response when only two diffusers were operating. Sulphur oxidizers responded in a manner indicating that mixing favors their production.

7. Zooplankton extended their vertical habitat but had little change in composition. There is no measured response by the fish population to the brief period of mixing.

8. Increased phytoplankton production and standing crop.

9. Sediment oxygen demands remained sufficiently high to maintain an oxygen stress situation throughout the harbour. Selective sediment removal is suspected to cause temporal stress situations by increasing the dissolved oxygen demand and turbidity.

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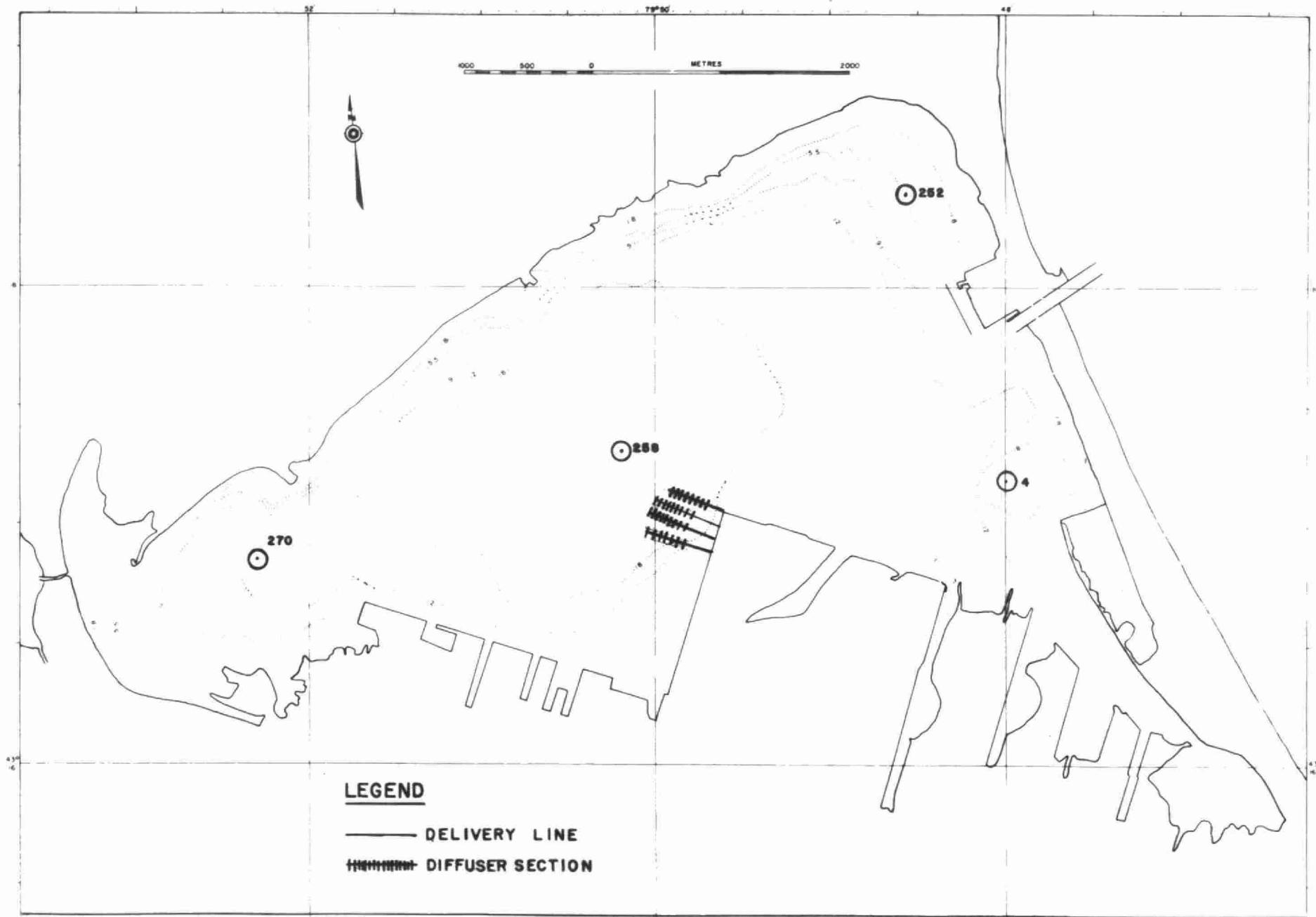
FIGURE 1: HAMILTON HARBOUR ARTIFICIAL MIXING SYSTEM & SAMPLING STATIONS
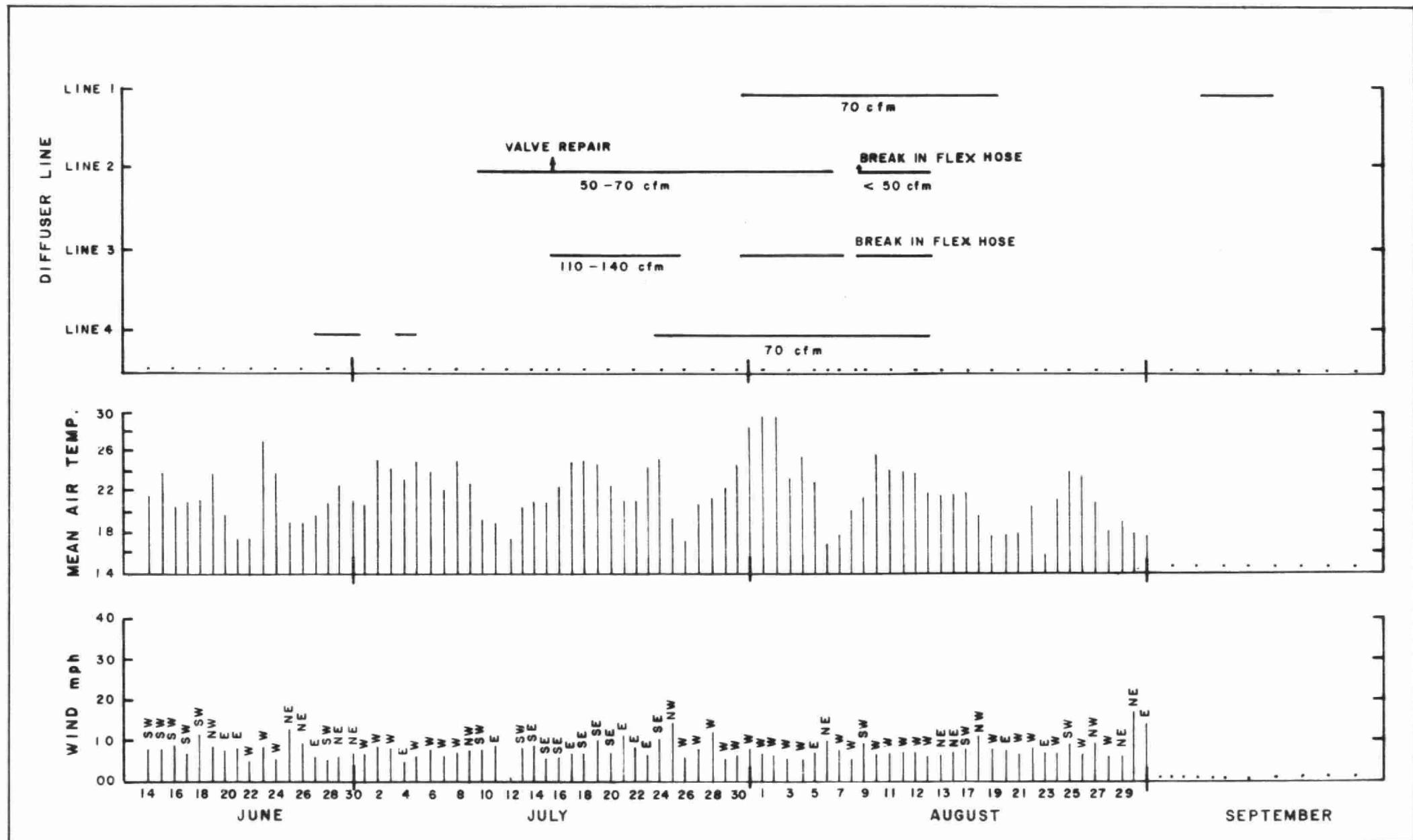
FIG. 2 OPERATION OF DIFFUSER LINES WITH AMBIENT WIND AND MEAN TEMPERATURE DATA.

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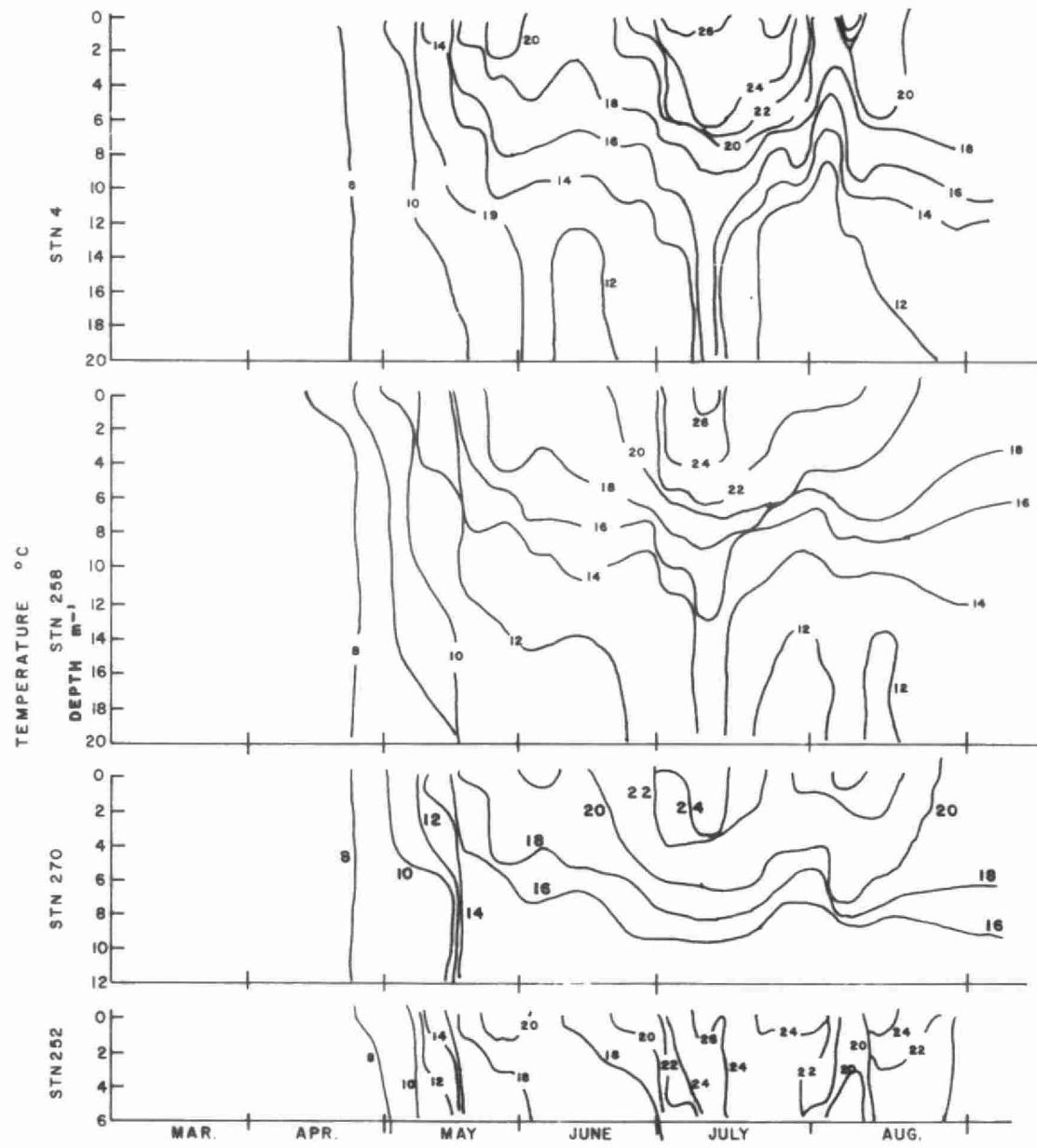
FIG. 3 THERMAL ISOPLETHS °C AT STATIONS 4, 258, 270, AND 252.
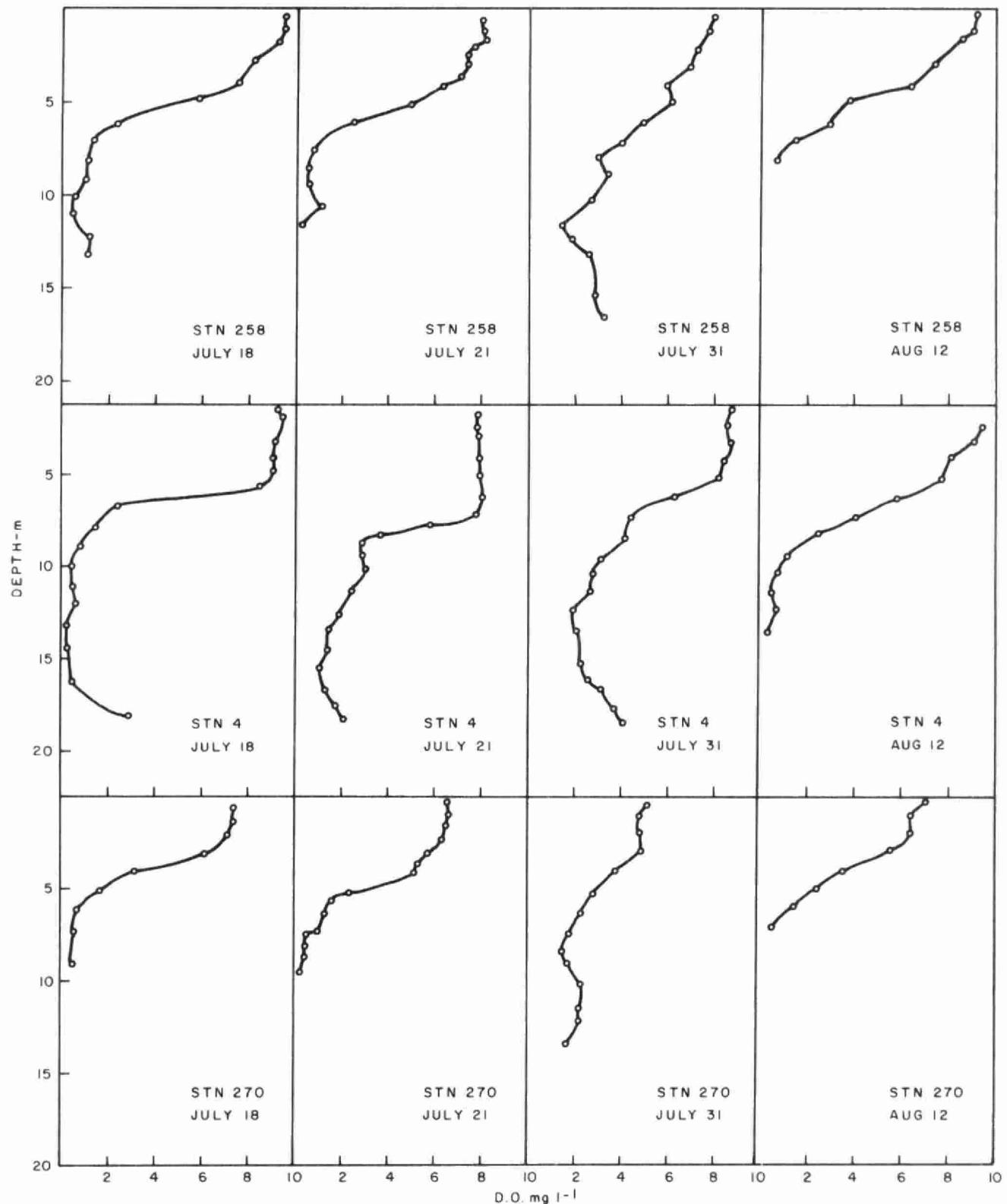
FIG. 4 DISSOLVED OXYGEN— DEPTH PROFILES DURING THE MIXING PERIOD. (mg/l).
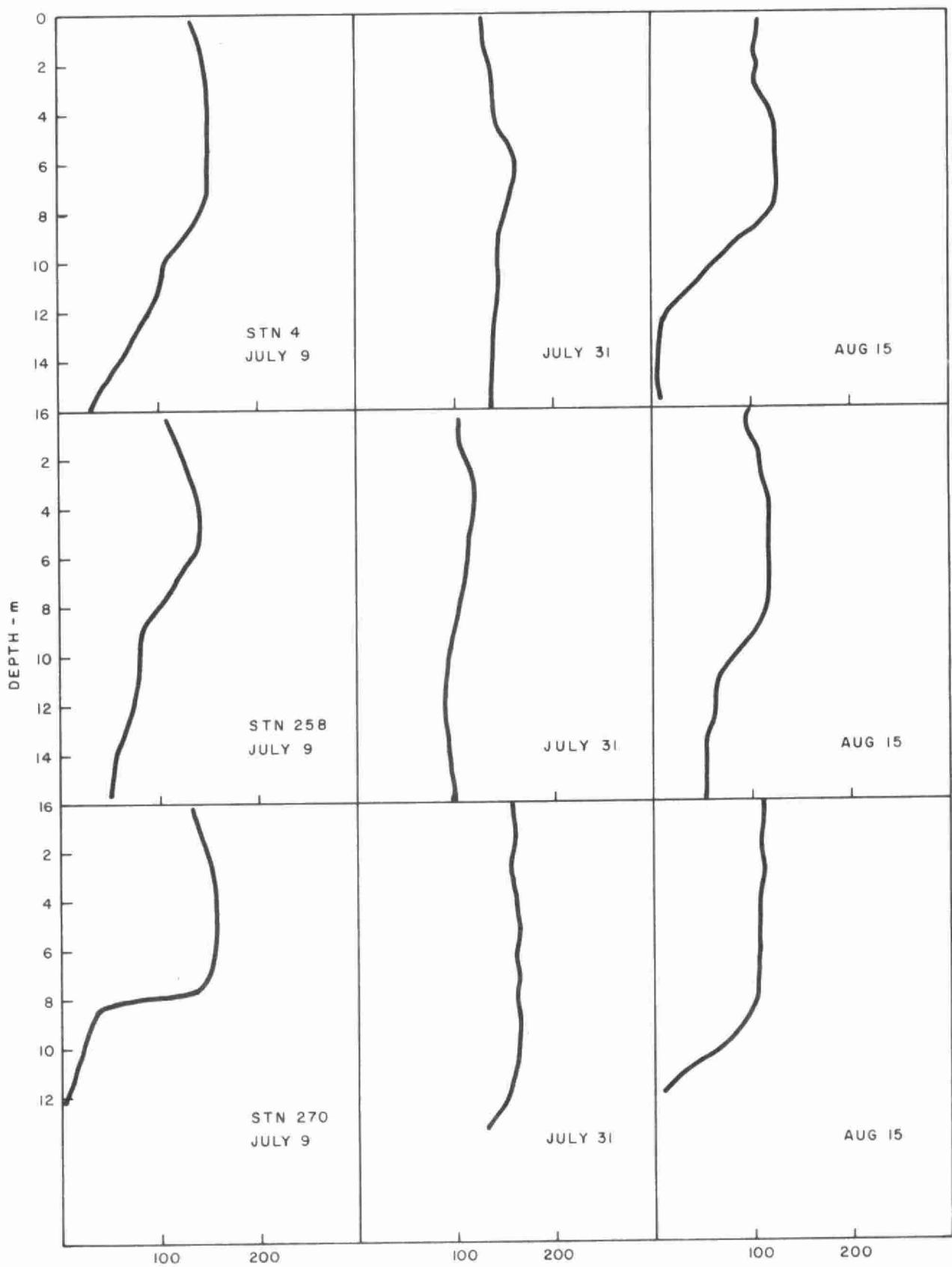
FIG. 5 REDOX POTENTIAL (mu) — DEPTH PROFILES DURING MIXING PERIOD.
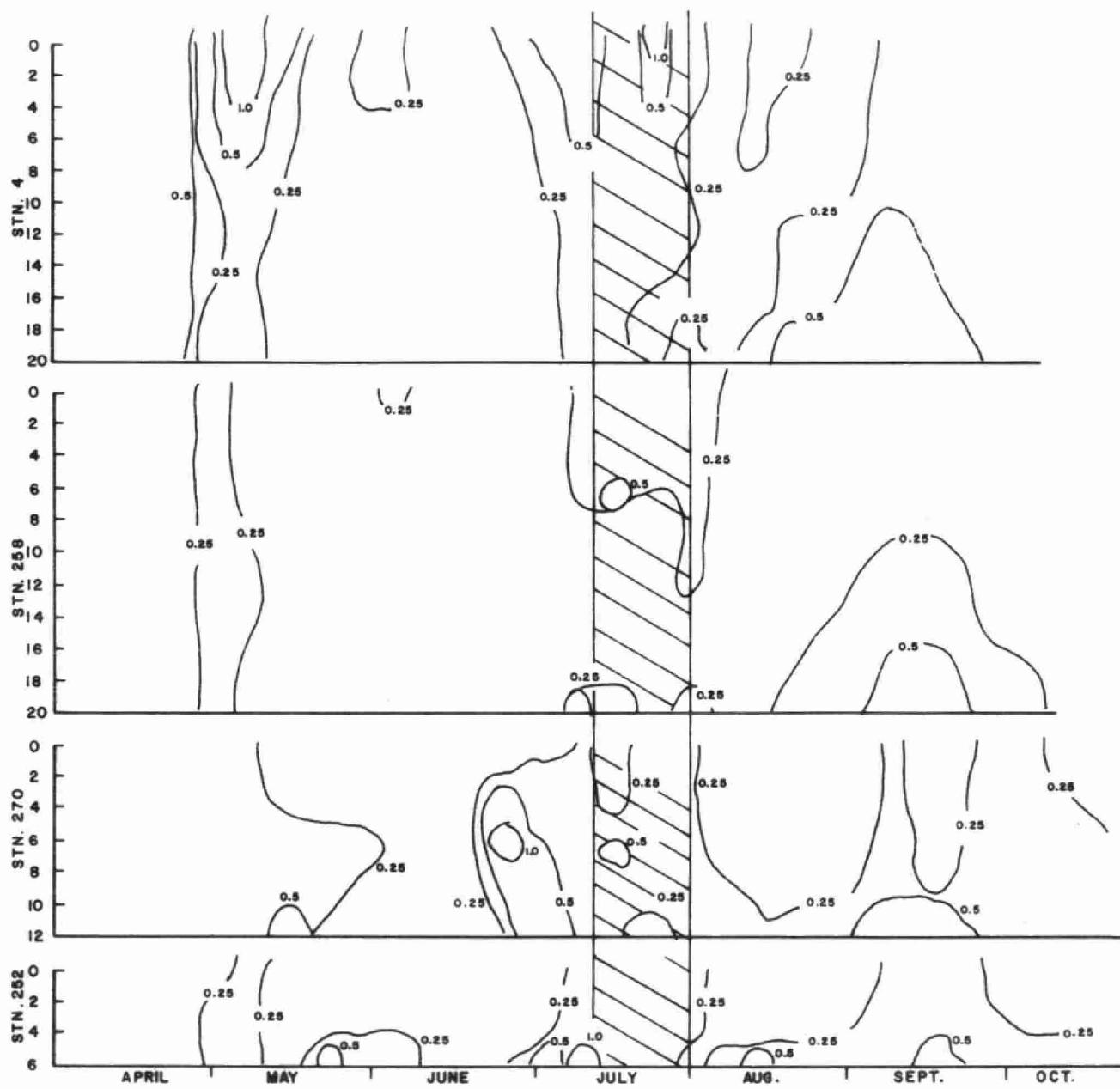
FIG. 6 VERTICAL AND TEMPORAL DISTRIBUTION OF IRON (mg/l) AT STATION 4, 258, 270, AND 252.
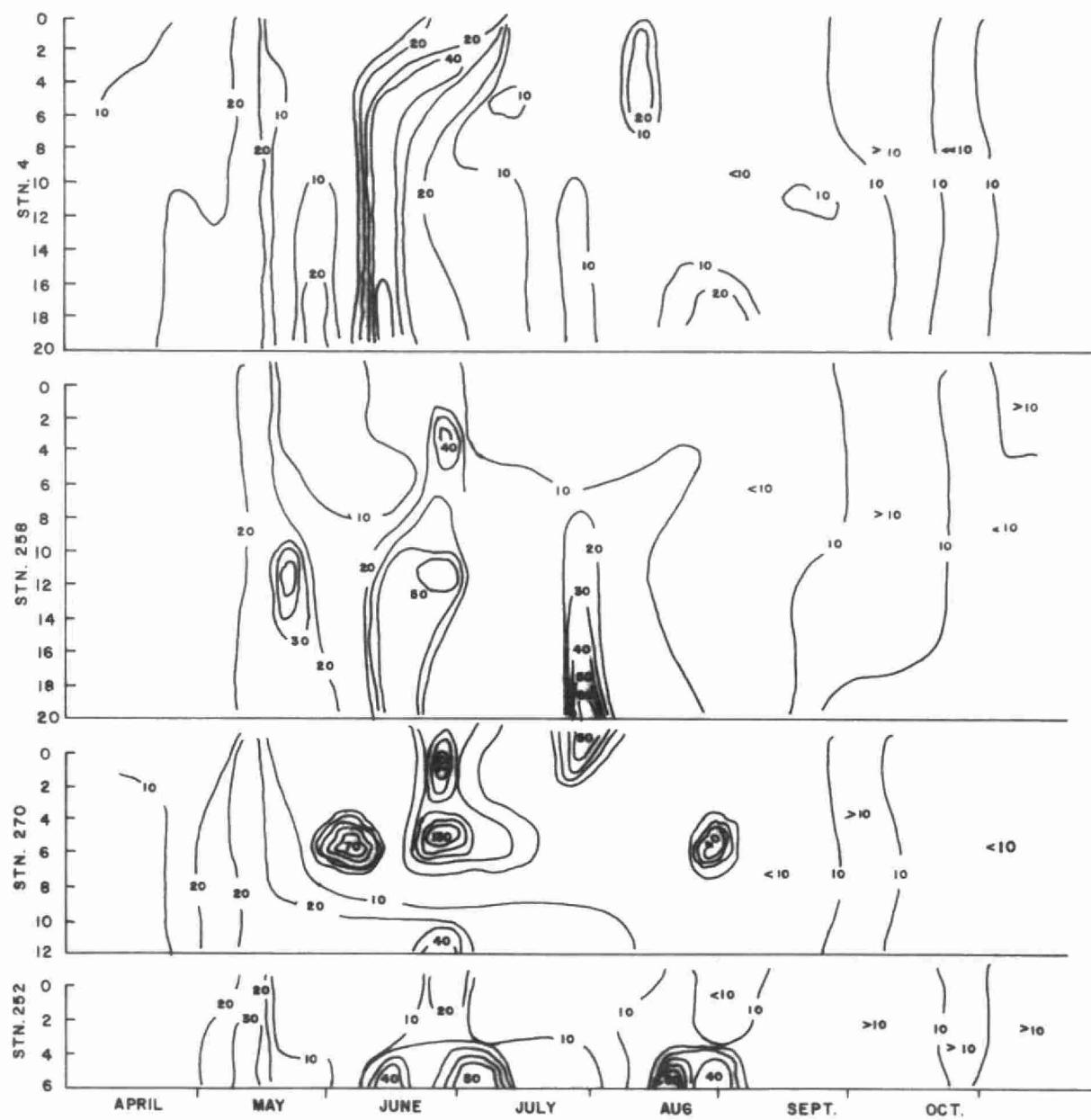
FIG. 7 VERTICAL AND TEMPORAL DISTRIBUTION OF SOLUBLE REACTIVE PHOSPHORUS (μg/l)
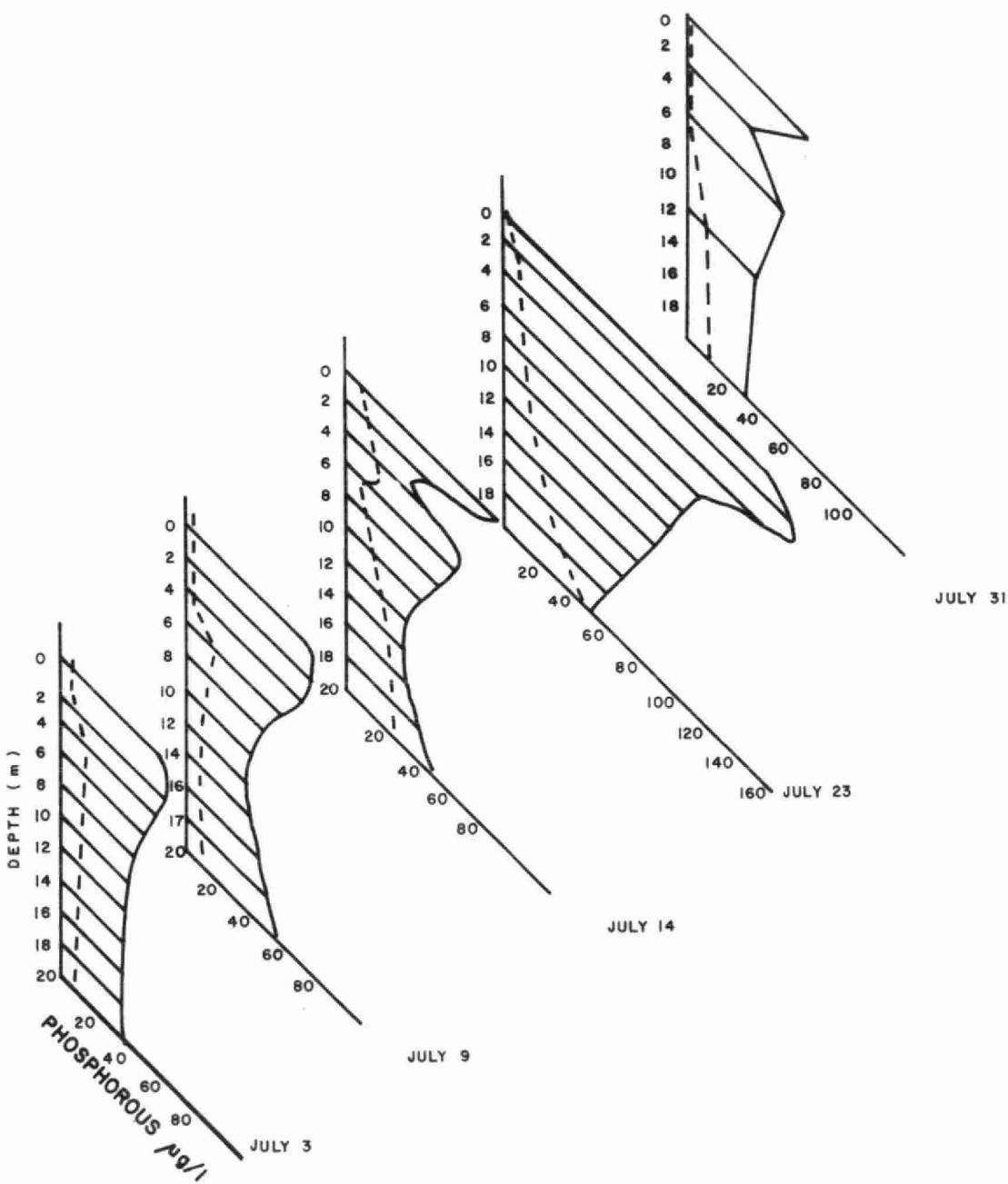
FIG. 7b VERTICAL DISTRIBUTION OF TOTAL AND DISSOLVED REACTIVE PHOSPHORUS AT
STATION 258.
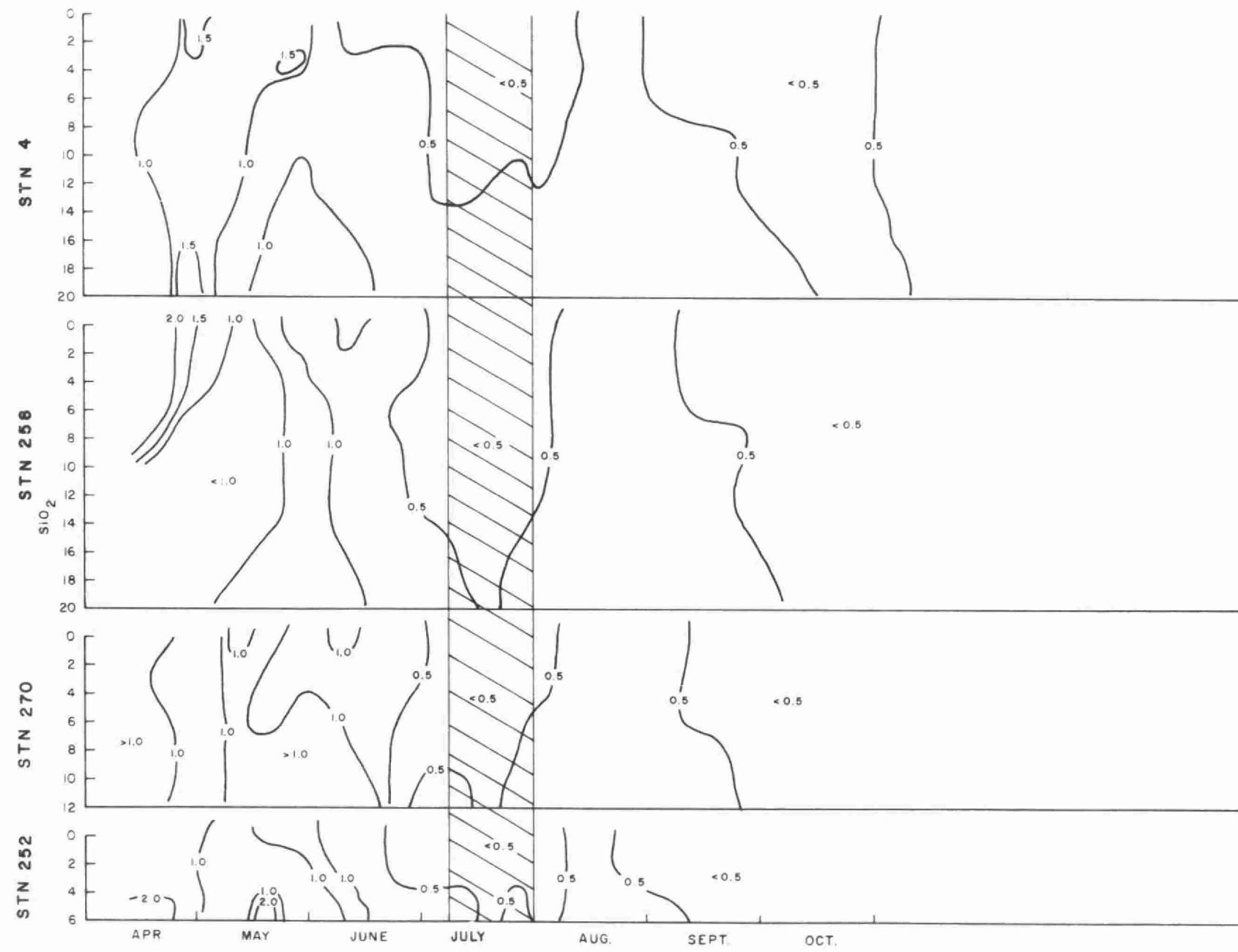
FIG. 8 VERTICAL AND TEMPORAL DISTRIBUTION OF DISSOLVED REACTIVE SILICATES (mg/l) AT
STATIONS 4, 270, 258, 252, 1975.
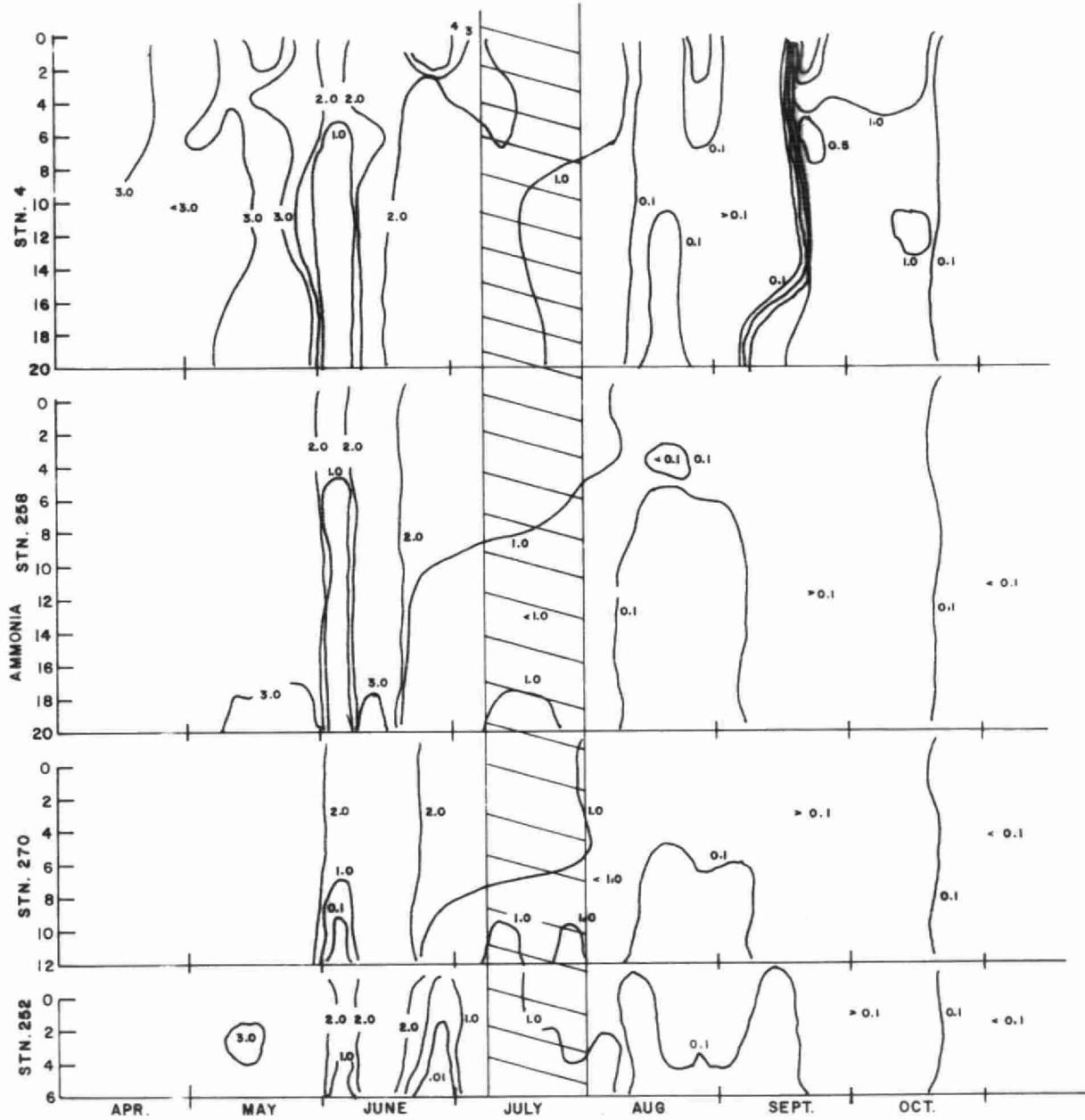
FIG. 9   TEMPORAL AND VERTICAL DISTRIBUTION OF NH$_4$ (mg/l).
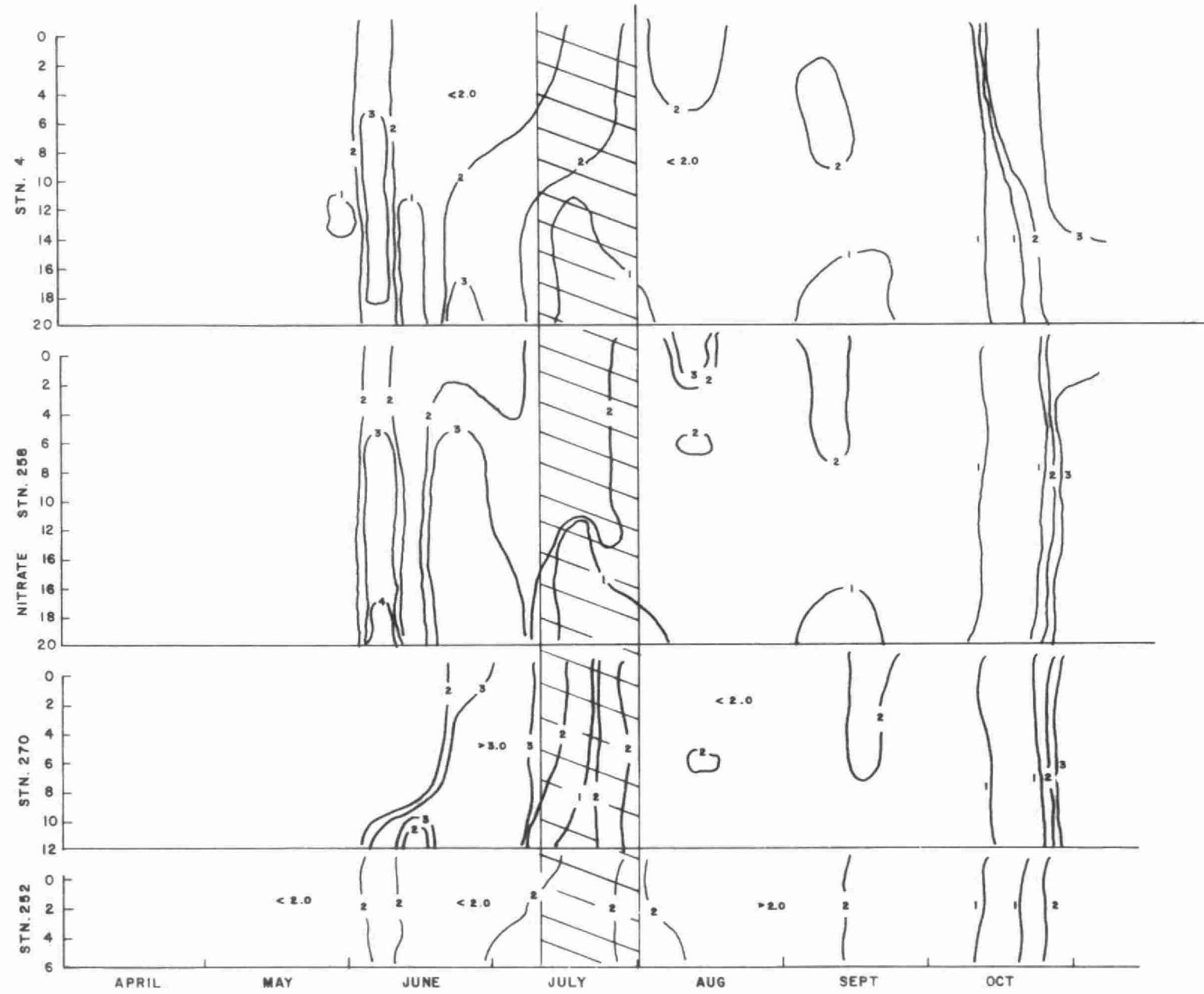
FIG. 10 VERTICAL AND TEMPORAL DISTRIBUTION OF NO_3 (mg/l) AT STATIONS 4, 258, 270, AND 252.
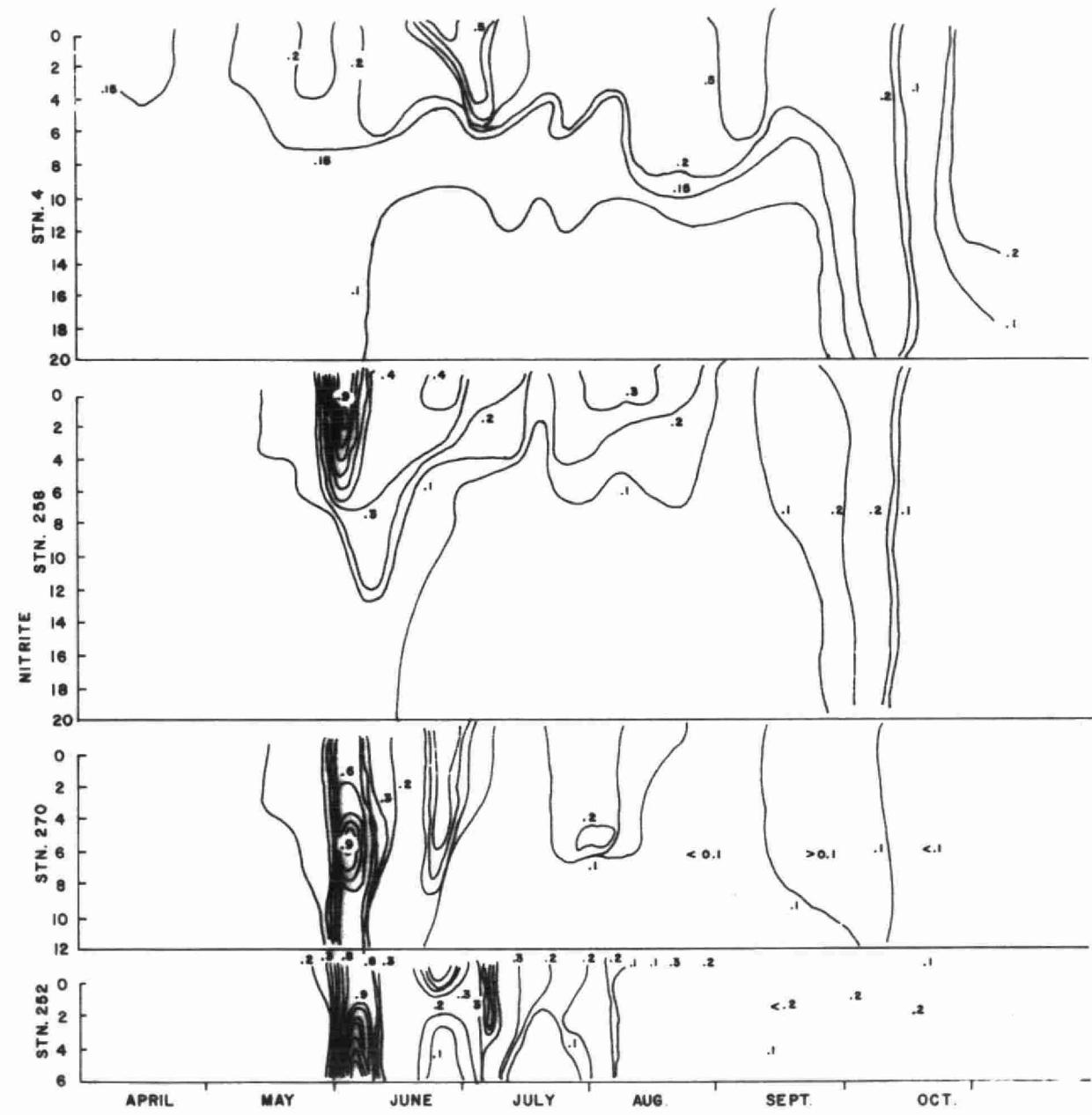
FIG. II VERTICAL AND TEMPORAL DISTRIBUTION OF NITRITES (mg/l).
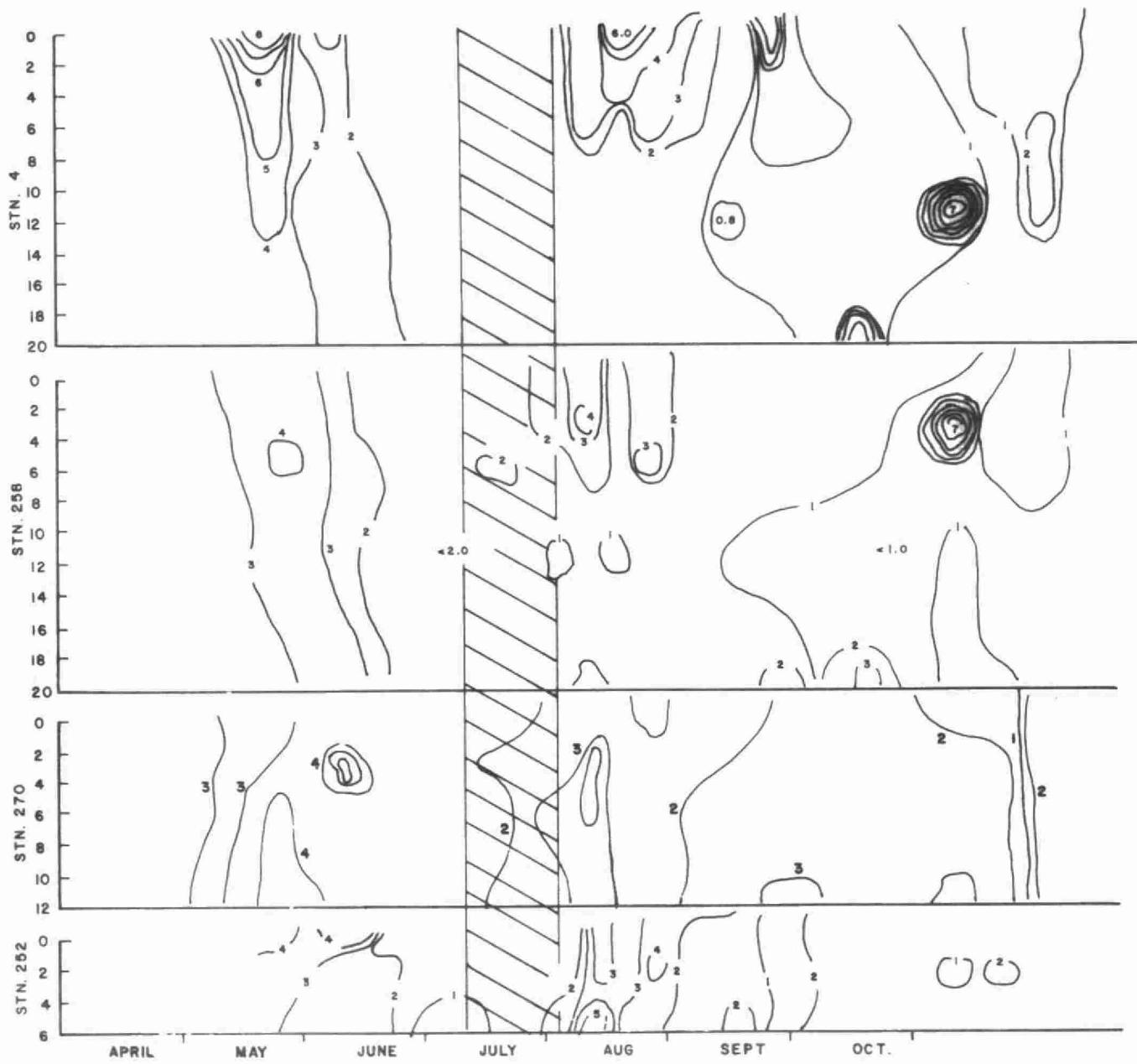
FIG. 12 VERTICAL AND TEMPORAL DISTRIBUTION OF TURBIDITY (FTU).

B-32
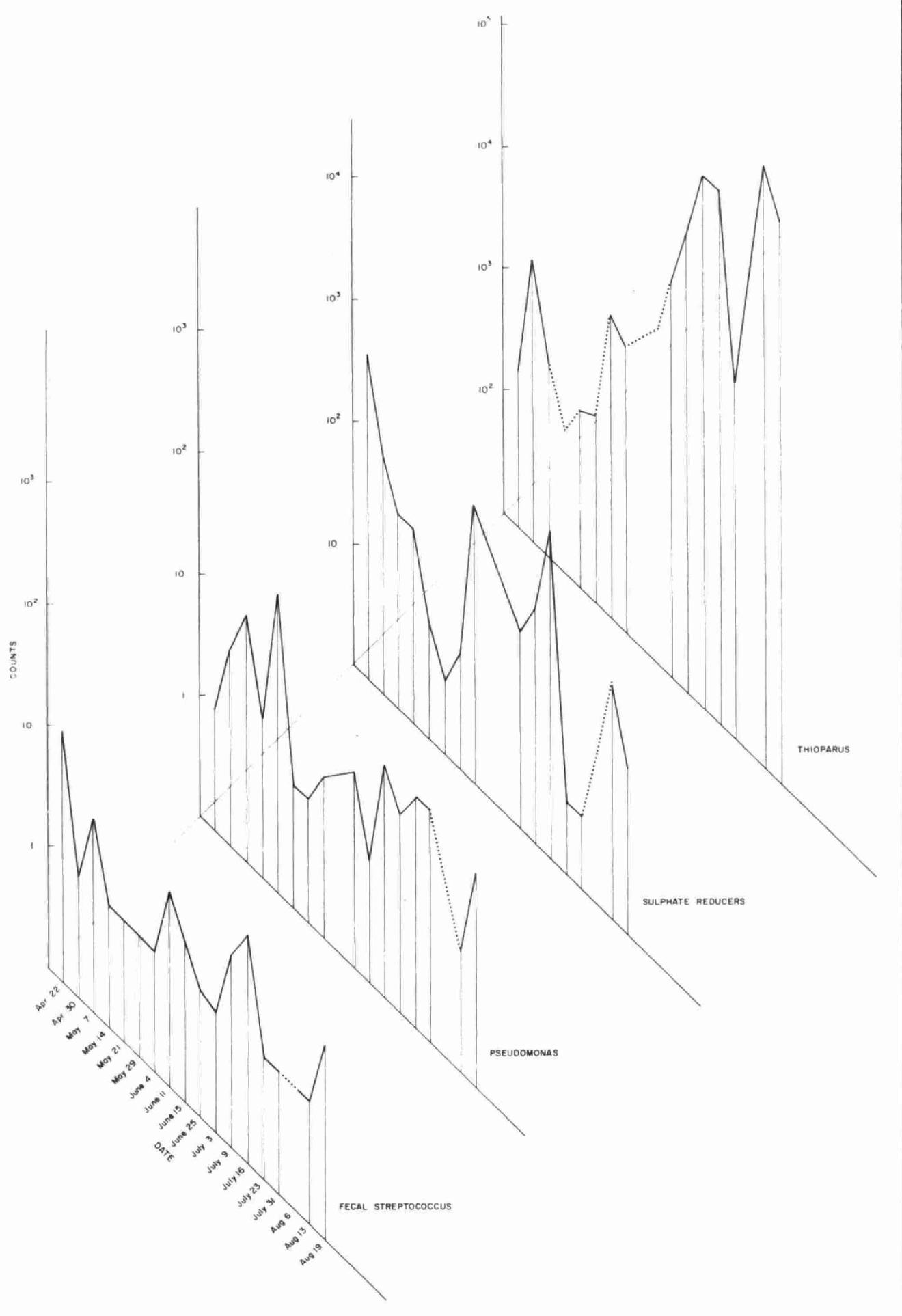
Figure 13a. Bacterial Populations at Station 258, 1975 (surface).
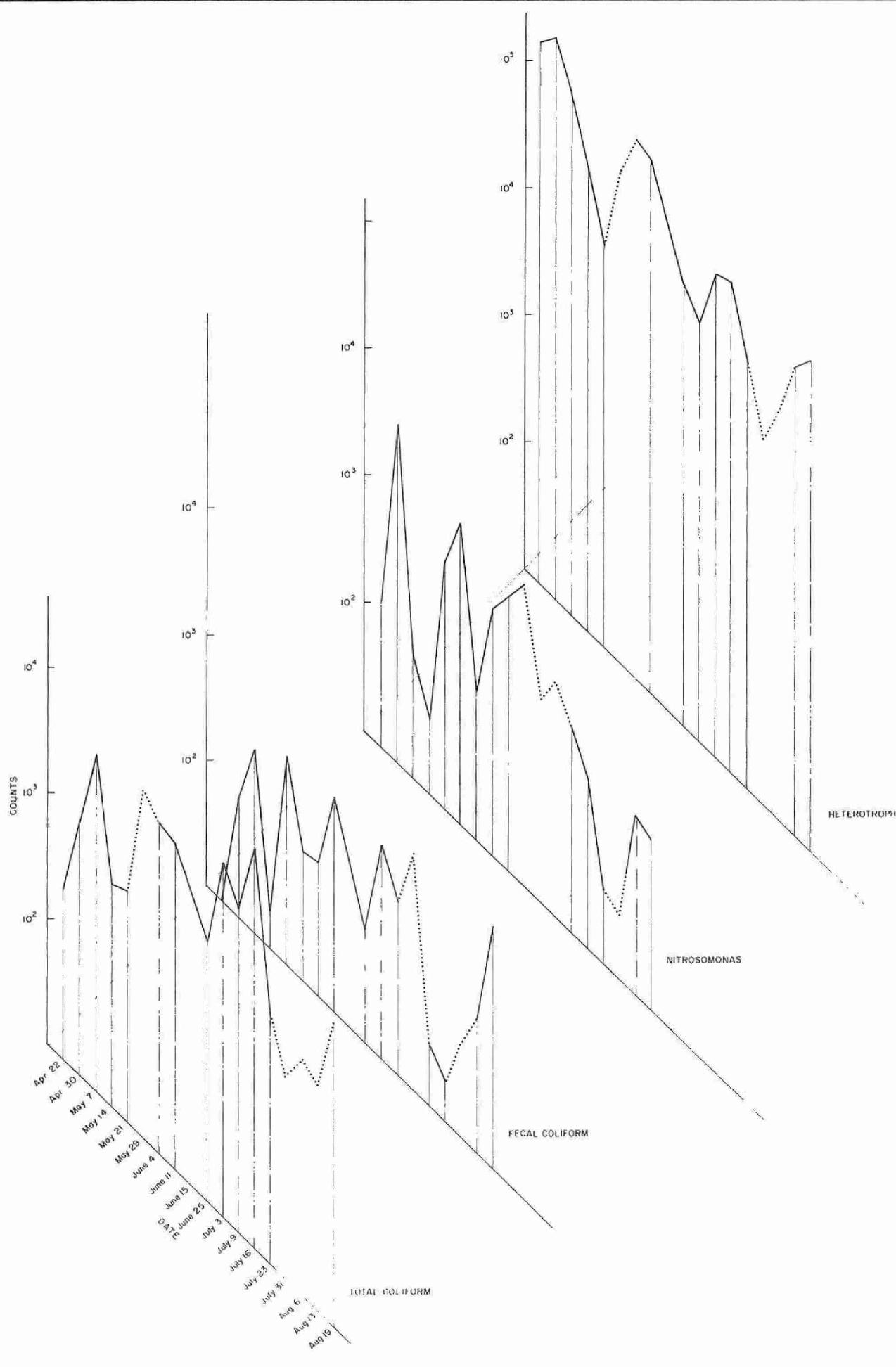
Figure 13 b. Bacterial Populations at Station 258, 1975 (surface).

FIG. 13c BACTERIAL POPULATION AT STN. 258, 1975 (BOTTOM).
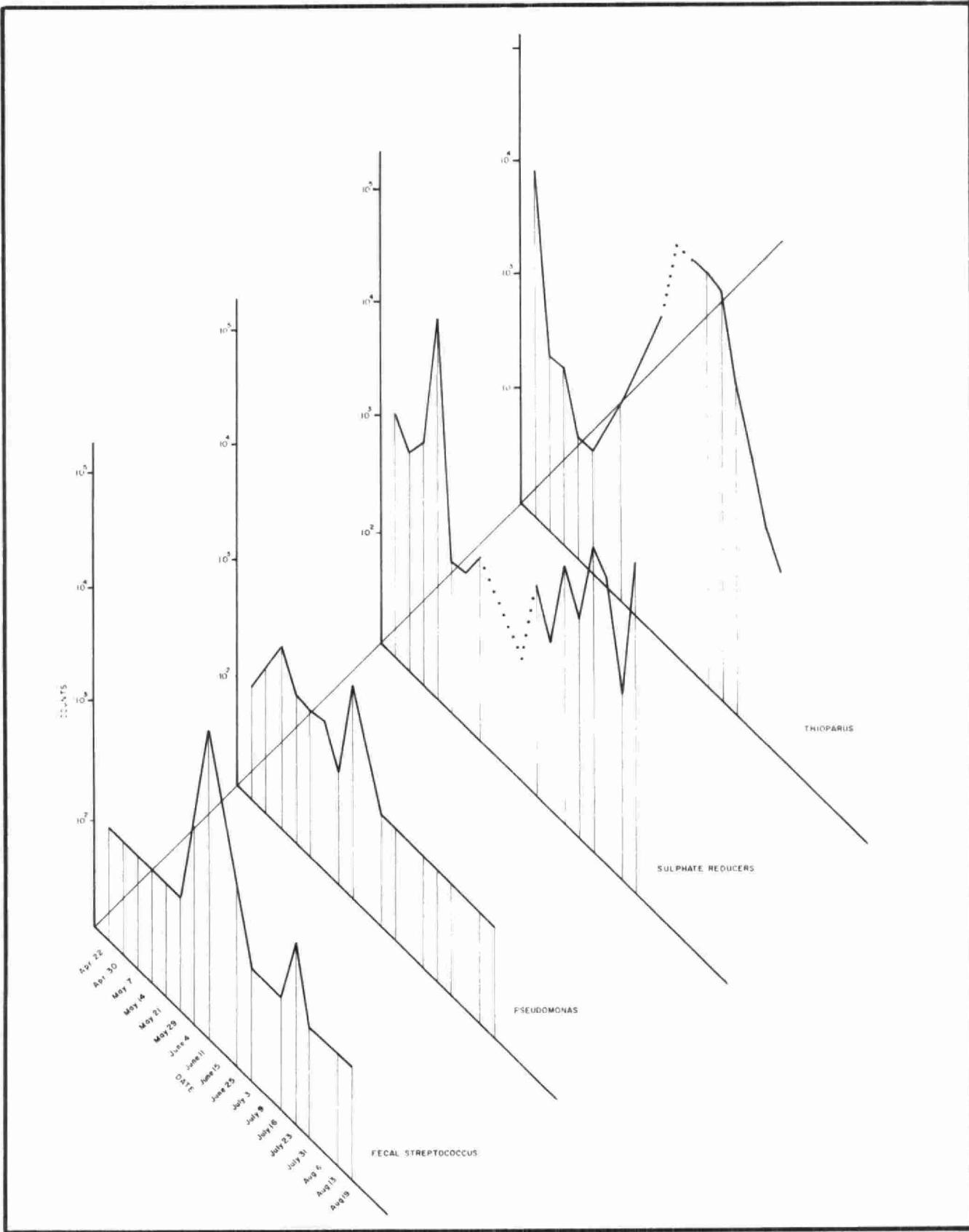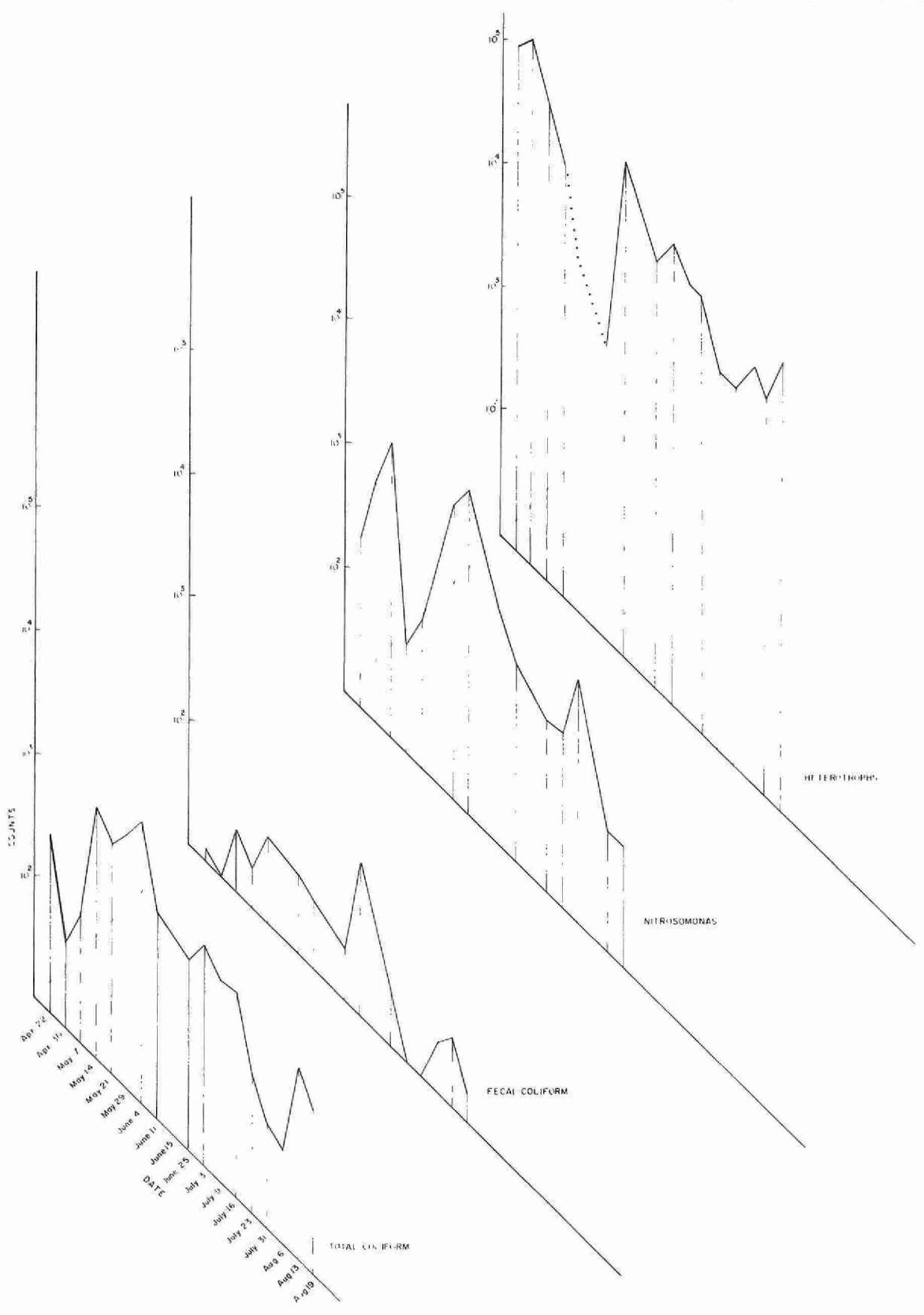
FIG. 13d BACTERIAL POPULATION AT STN. 258, 1975 (BOTTOM).

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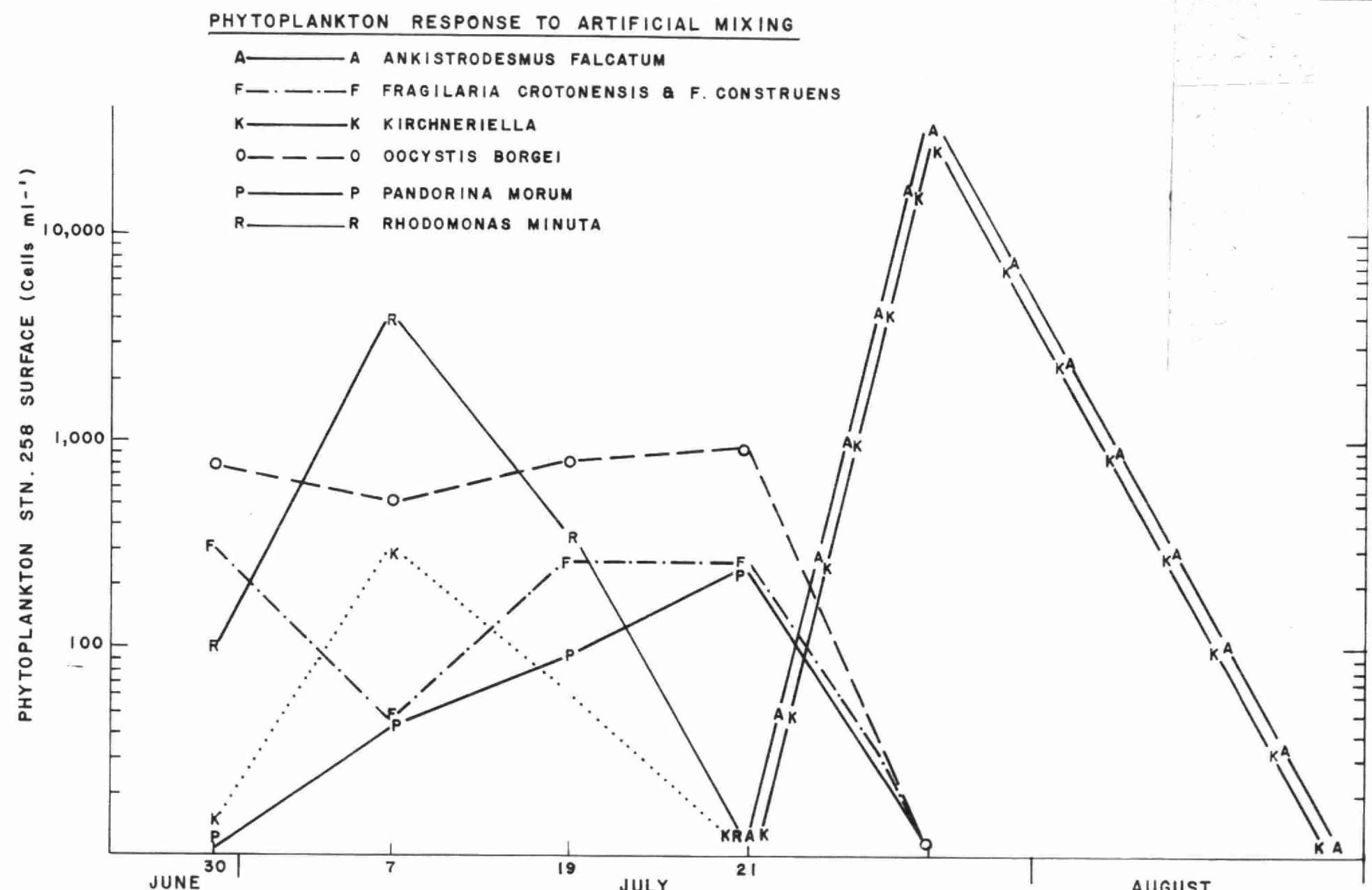
FIG. 14 PHYTOPLANKTON DISTRIBUTION (SURFACE) AT STATION 258, 1975 (CELLS/ml).
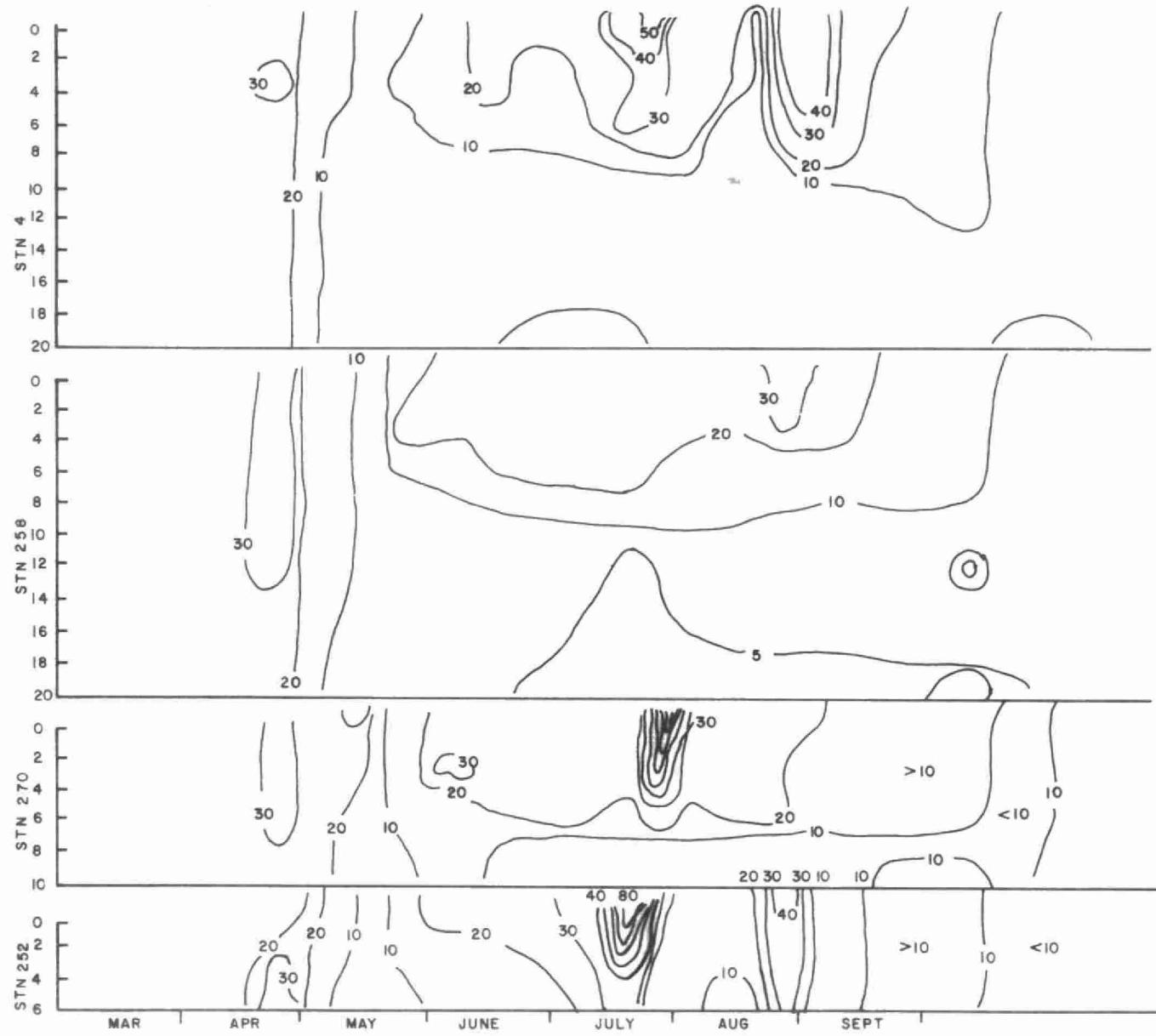
FIG. 15(a) VERTICAL AND TEMPORAL DISTRIBUTION OF CHLOROPHYL "A" (µg/l) AT STATIONS 4, 258, 270, AND 252.
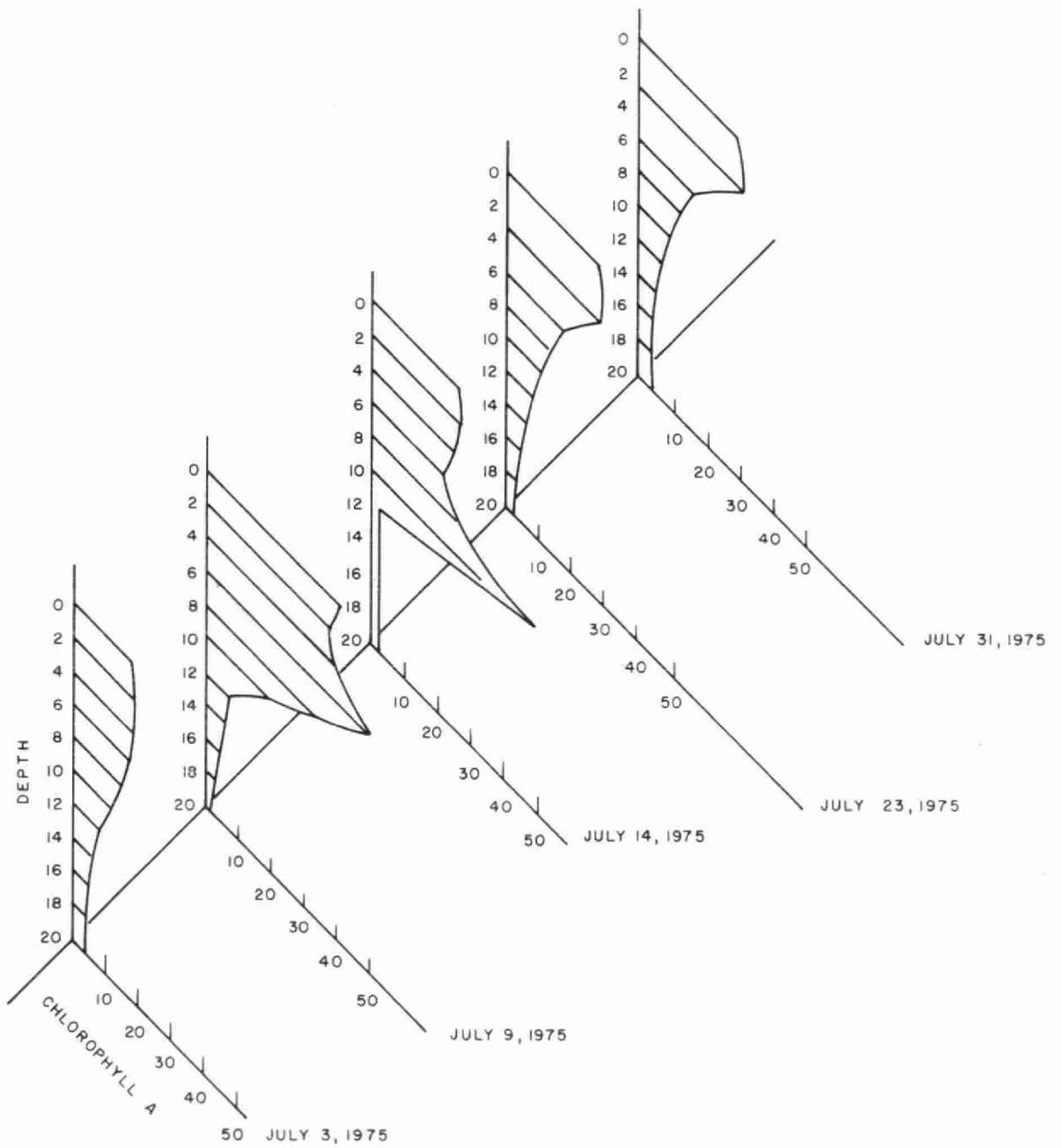
FIG. 15 b   CHLOROPHYLL   DISTRIBUTION   DURING   THE   MIXING   PERIOD   AT   STATION   258,   1975.
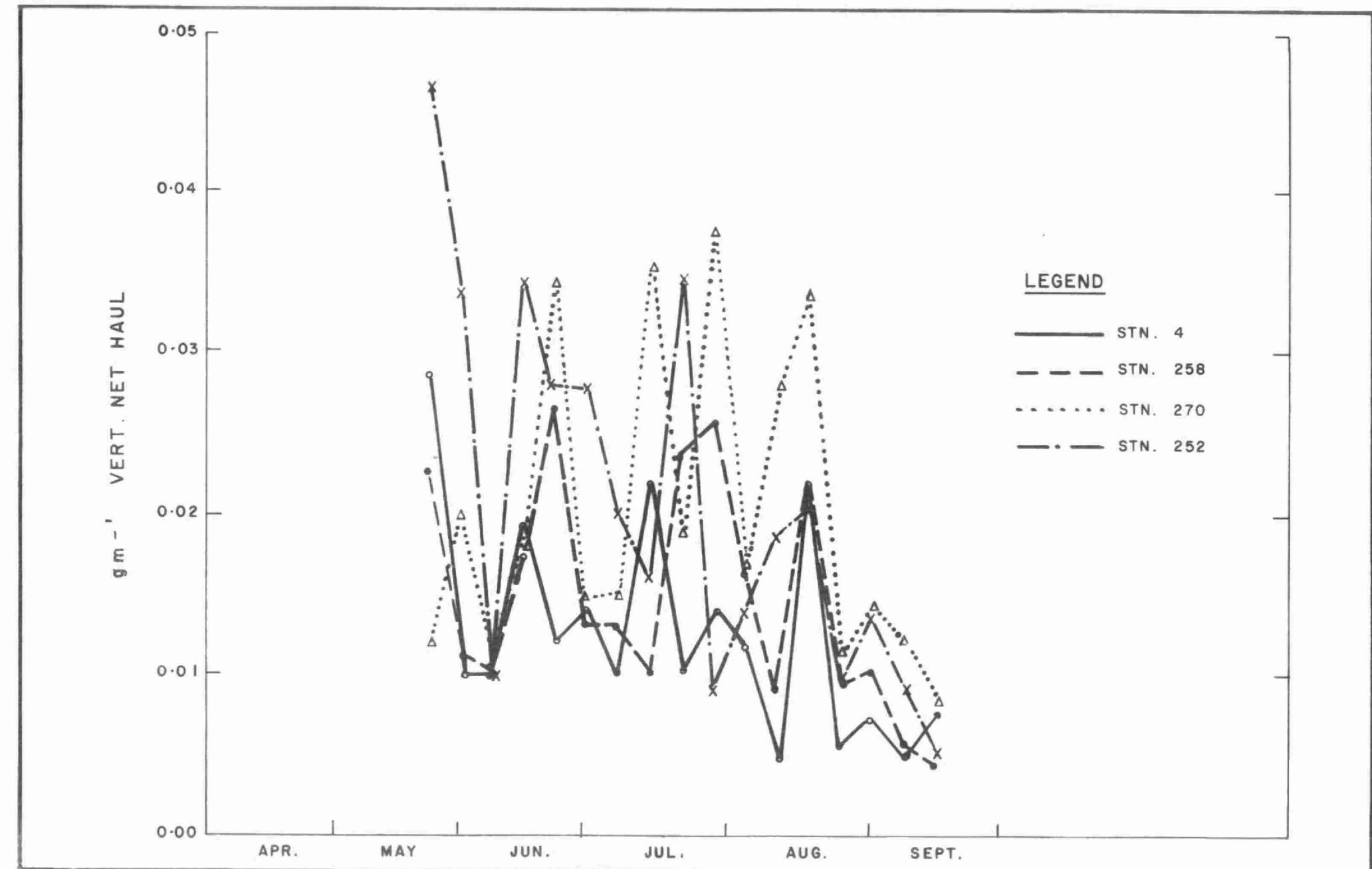
FIGURE 16: RELATIVE ZOOPLANKTON ABUNDANCE (gm⁻¹ VERTICAL NET HAUL AT STATIONS 4, 258, 270 & 252 — 1975

	DATE DUE		